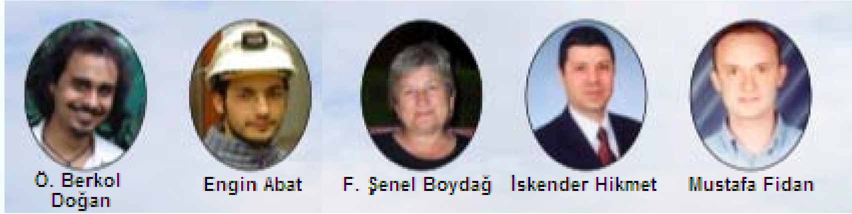
British Accelerator Science
&
Radiation Oncology Consortium


Engin Arik



A new accelerator for advanced research and cancer therapy

Ken Peach
John Adams Institute for Accelerator Science
University of Oxford and Royal Holloway University of London

and

Particle Therapy Cancer Research Institute
(part of the James Martin 21st Century School, Oxford)

International Conference on Particle Physics
In the memory of Engin Arik and her colleagues
Istanbul
30th October 2008

http://www.adams-institute.ac.uk   http://www.basroc.org.uk   Ken.Peach@adams-institute.ac.uk

Outline

- Introduction
- CANCER & Charged Particle Therapy
- The Neutrino Factory
- The ns-FFAG Accelerator

  (non-scaling Fixed-Field Alternating Gradient)

  EMMA

  PAMELA
- Summary

Introduction

- **There are more than 17,000 particle accelerators (> a few MeV) worldwide**
  - **Most are used in medicine**
    - **Linacs, cyclotrons, some synchrotrons…**
  - **Next most common in industry**
    - **Ion implantation etc**
  - **Synchrotron Radiation Sources**
    - **Mostly synchrotrons, coming soon - linacs**
  - **Neutron and radionuclide sources**
    - **Linacs, cyclotrons, synchrotrons, something weird**

and

- **For particle physics!**
  - **A few big synchrotrons (& colliders)**
    - **Often with Linacs at the front end**
  - **And coming soon (maybe) the ILC**

British Accelerator Science
&
Radiation Oncology Consortium

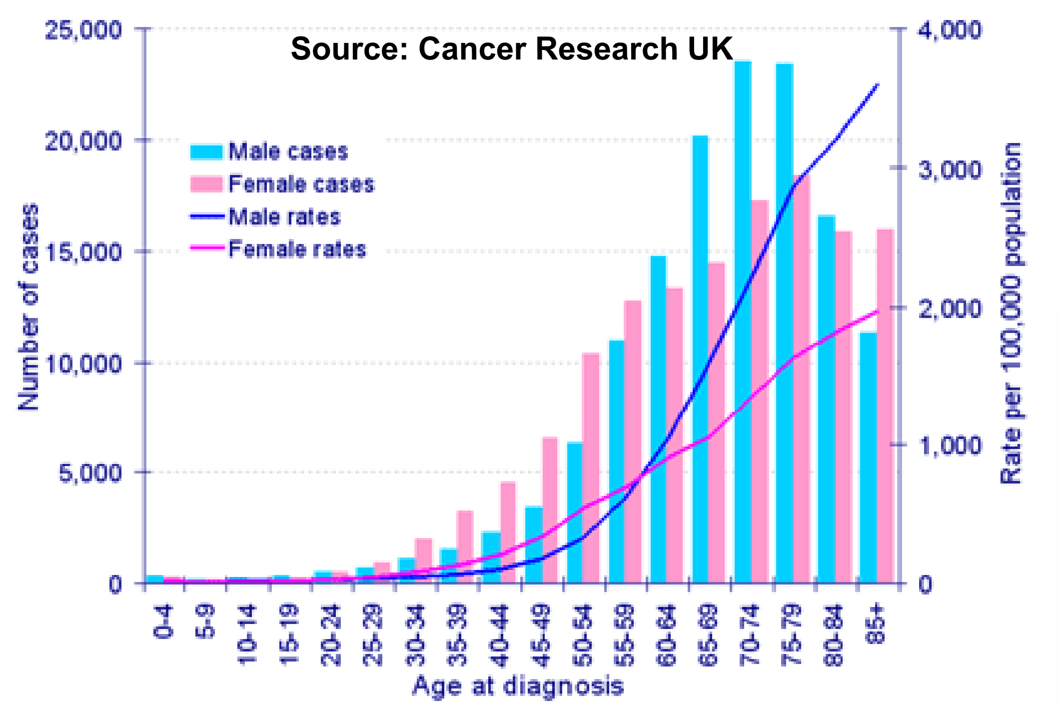
CANCER

Charged Particle Therapy
(Protons and Light Ions)

http://www.adams-institute.ac.uk http://www.basroc.org.uk Ken.Peach@adams-institute.ac.uk

Incidence of Cancer in the UK

Figure 2.1: Numbers of new cases and age-specific incidence rates by sex, all neoplasms (exc NMSC), UK 2002


Source: Cancer Research UK

- **12.5% probability, all types (except skin cancer) by 65**
  - **Rises to more than 1/3rd for whole-life**
  - **Around half are associated with specific risks**
  - **Statistically, some will be close to sensitive tissue**
    - **and difficult to treat surgically or chemically**

An important statistic

> **" Radiotherapy remains a mainstay in the treatment of cancer. Comparison of the contribution towards cure by the major cancer treatment modalities shows that of those cured, 49% are cured by surgery,** 40% by radiotherapy **and 11% by chemotherapy".**
>
> RCR document BFCO(03)3, (2003).

Chemotherapy provides by far the smallest contribution towards cancer cure yet is much more expensive than radiotherapy and generates a disproportionately large research and media interest.

Roger Dale, Hammersmith Hospital and Imperial College

Development of Cancer Radiotherapy

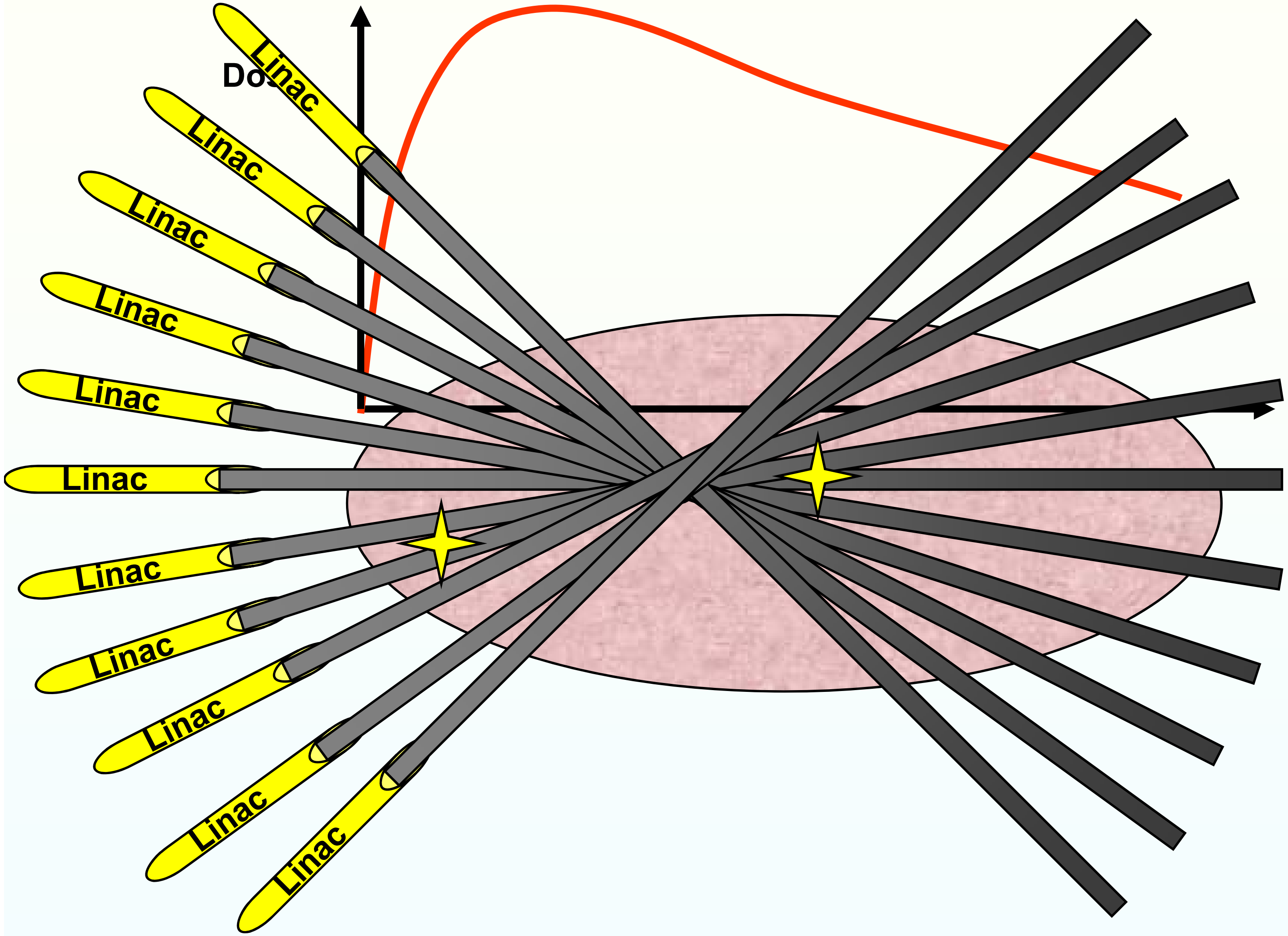
- 1895 : Konrad Rontgen's X-rays
- 1898 - Marie Curie's Radium
- Radium and x-ray machines used to treat cancer
- Most current radiotherapy uses High energy X-ray beams from linear accelerators or 'linacs'
- These X-ray beams pass through entire thickness of body

Modern Linac

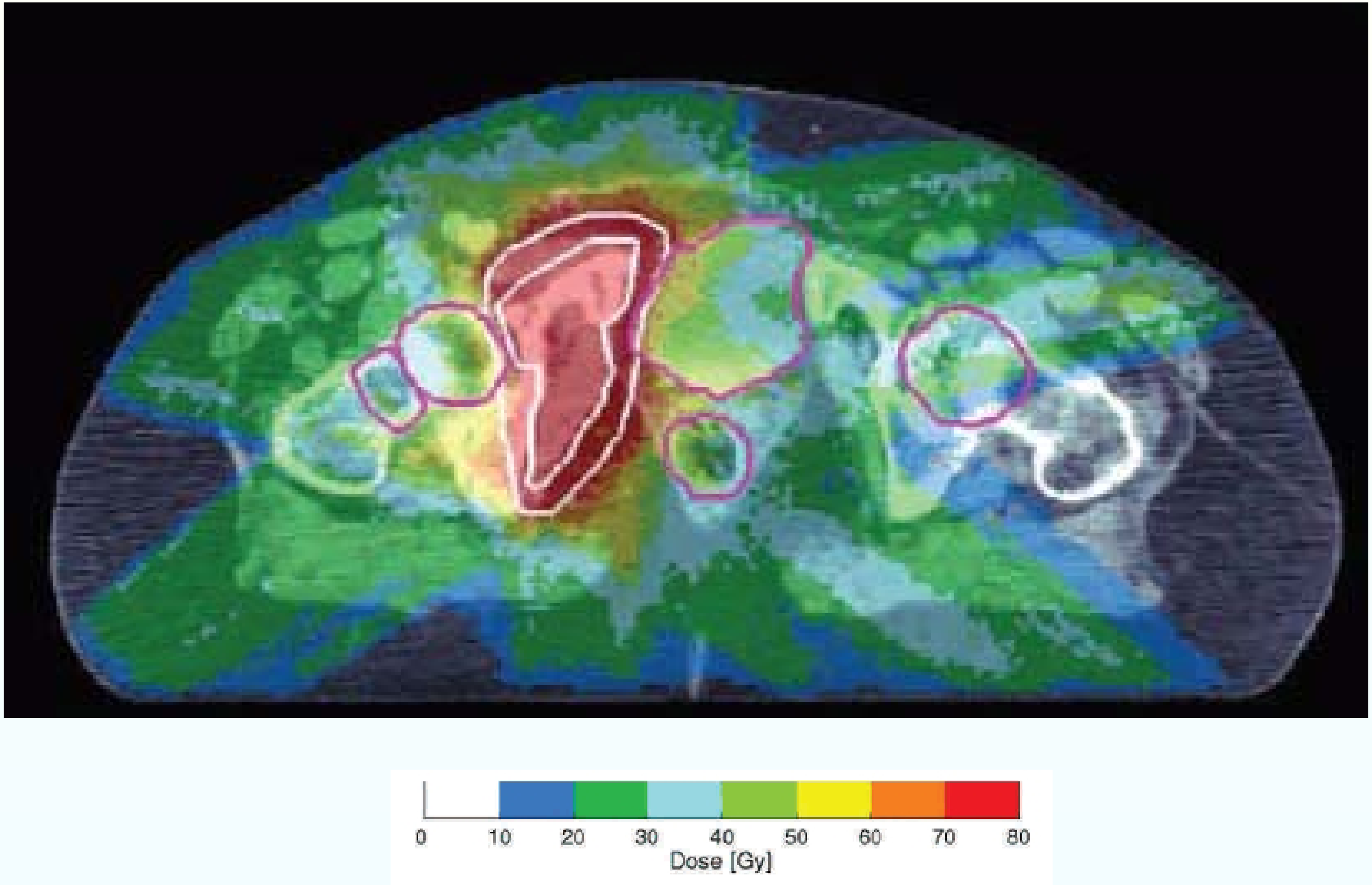
X-ray therapy began within months of Roentgen's discovery

1896 patient, Vienna: 70 years later

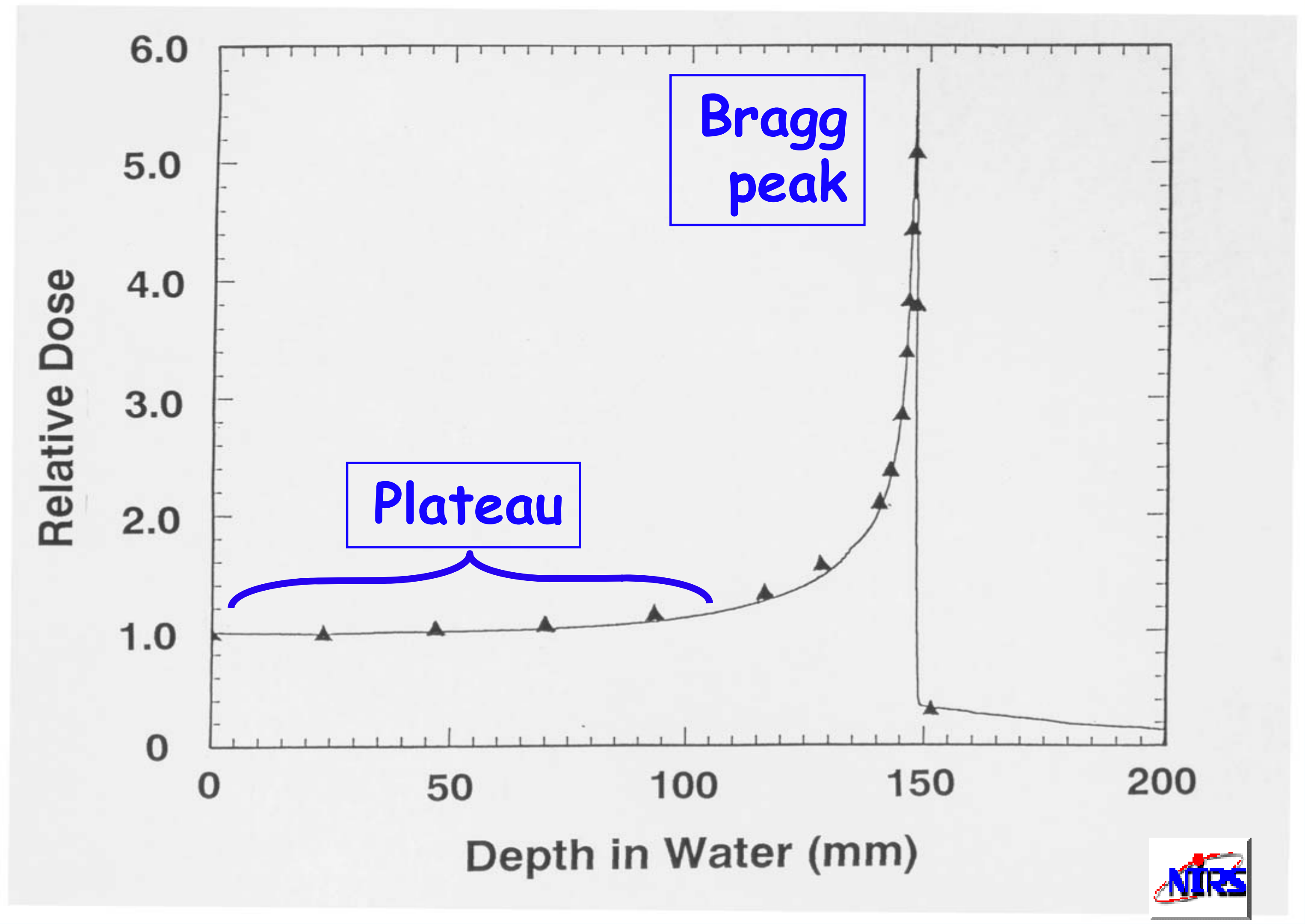
Curing Cancer with X-rays



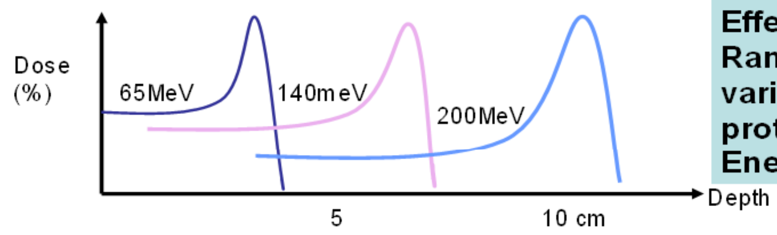
Intensity Modulated Radiation Therapy (IMRT)



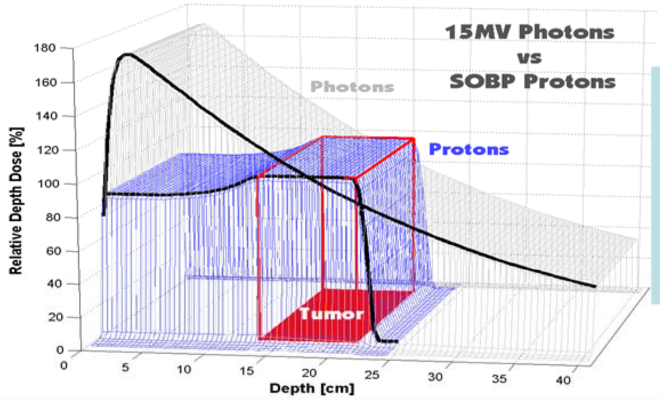
The Bragg Peak



Why use protons?

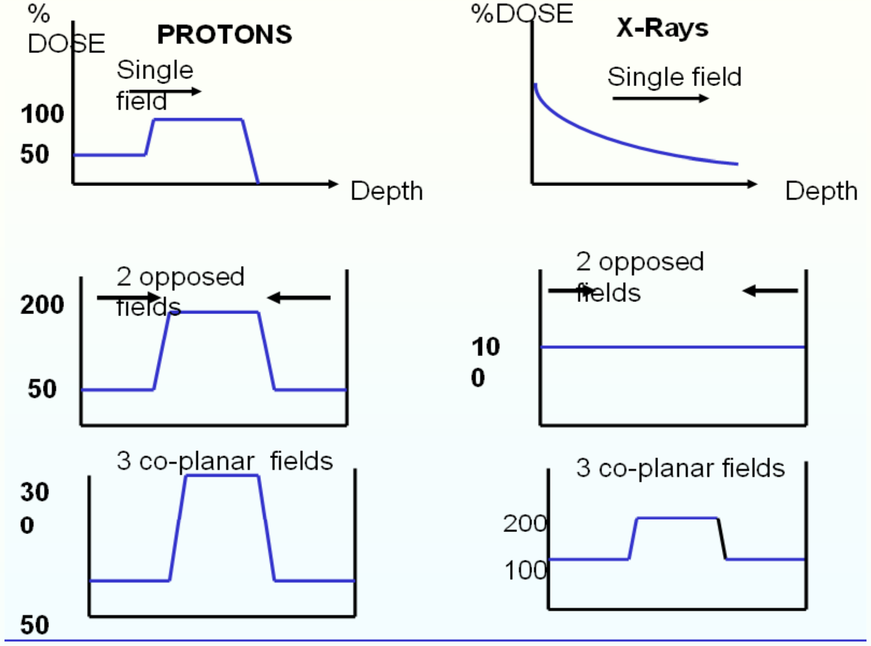


Effective Range varies with proton Energy

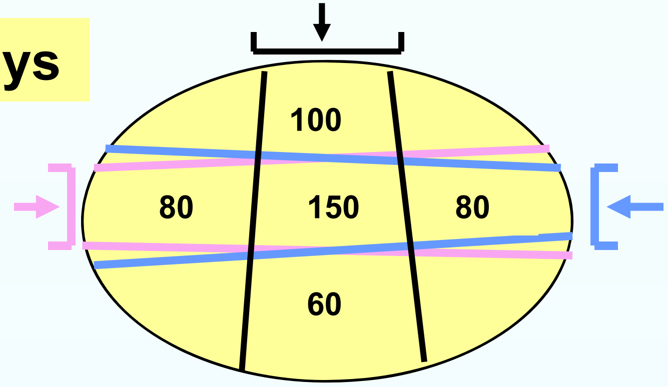


The 'spread-out' Bragg Peak – plateau effect

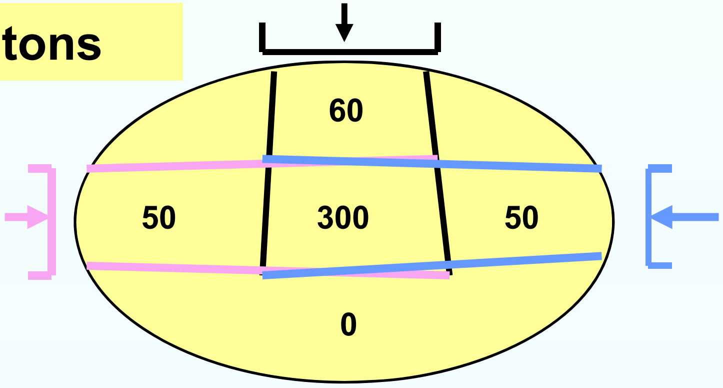
[SOBP]



X-Rays

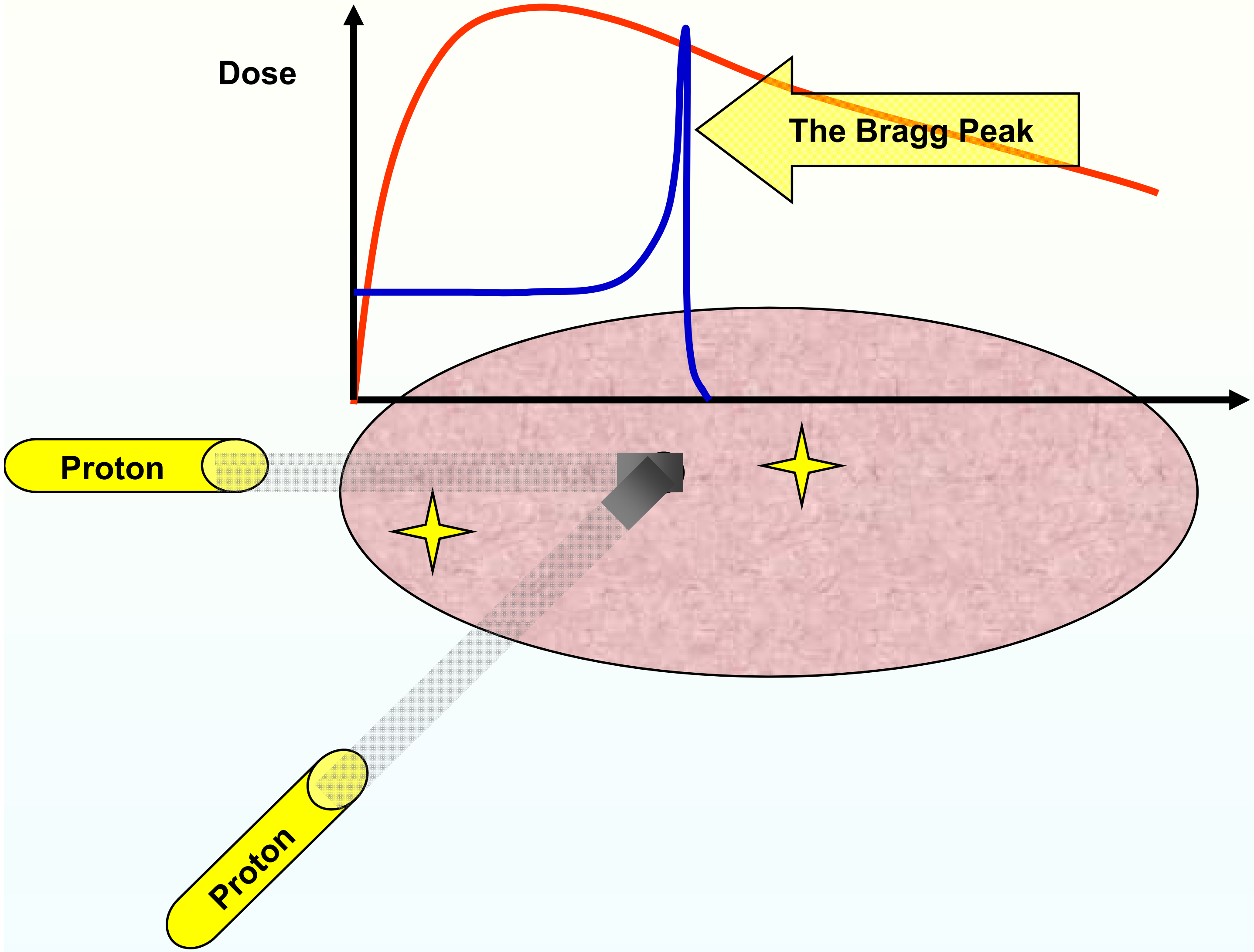


Protons

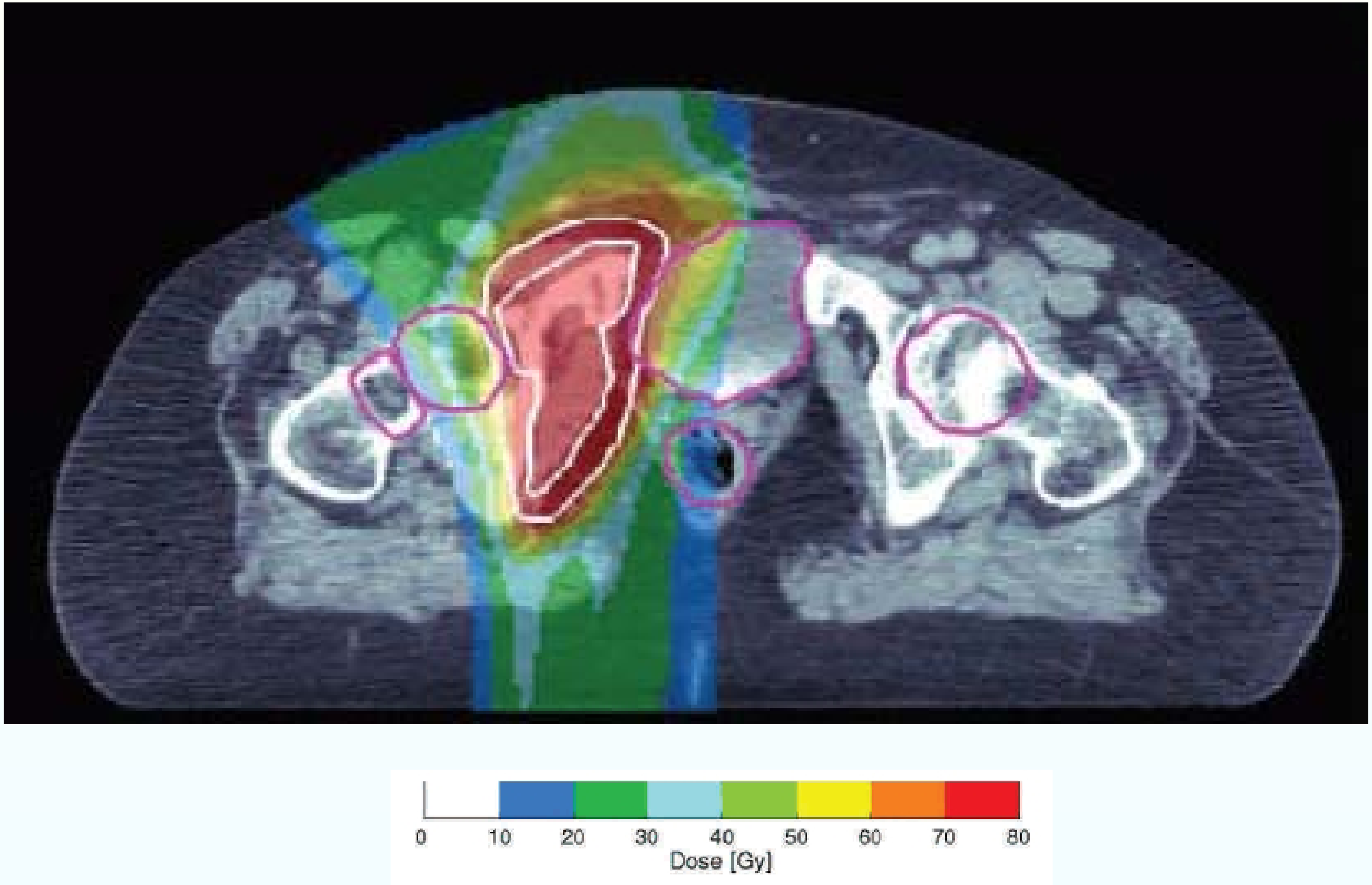


After Bleddyn Jones

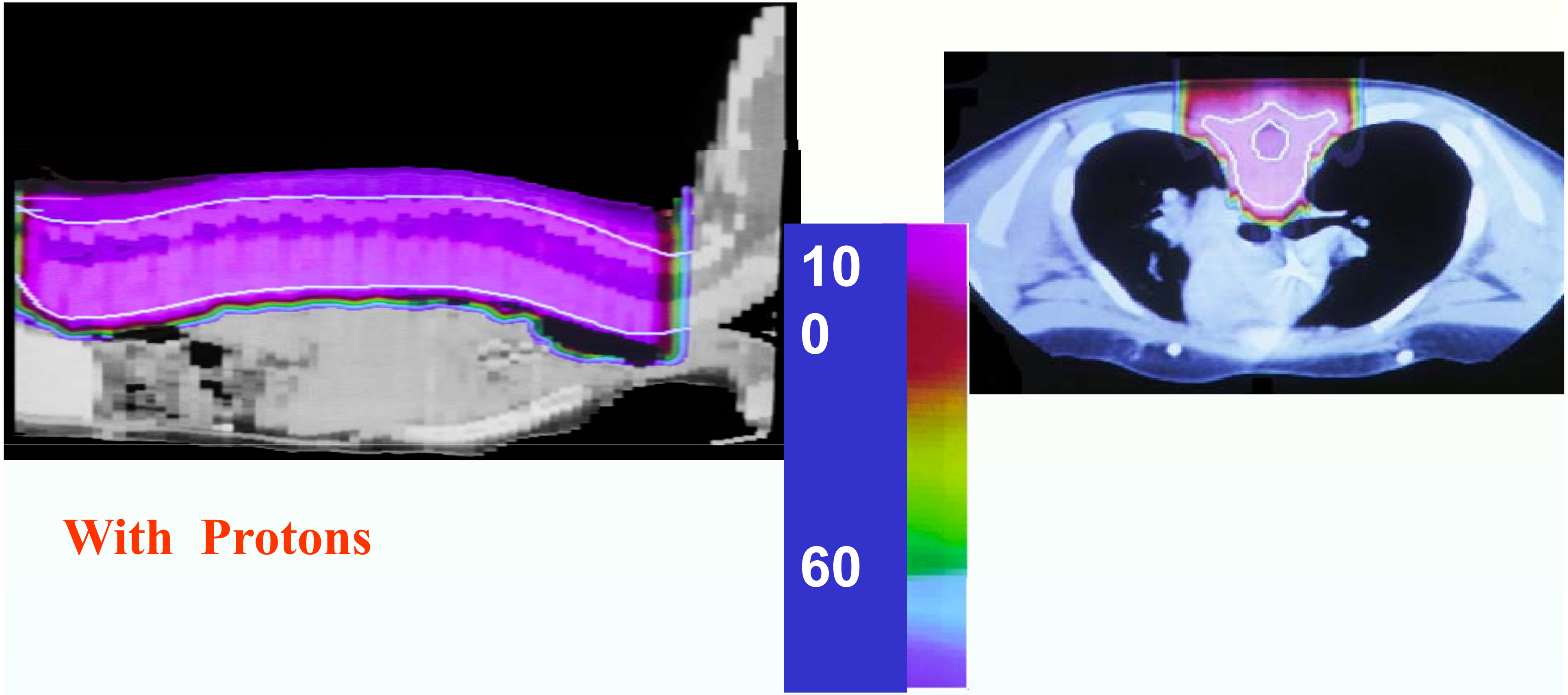
Can we do better?



Is it better?



Medulloblastoma in a child



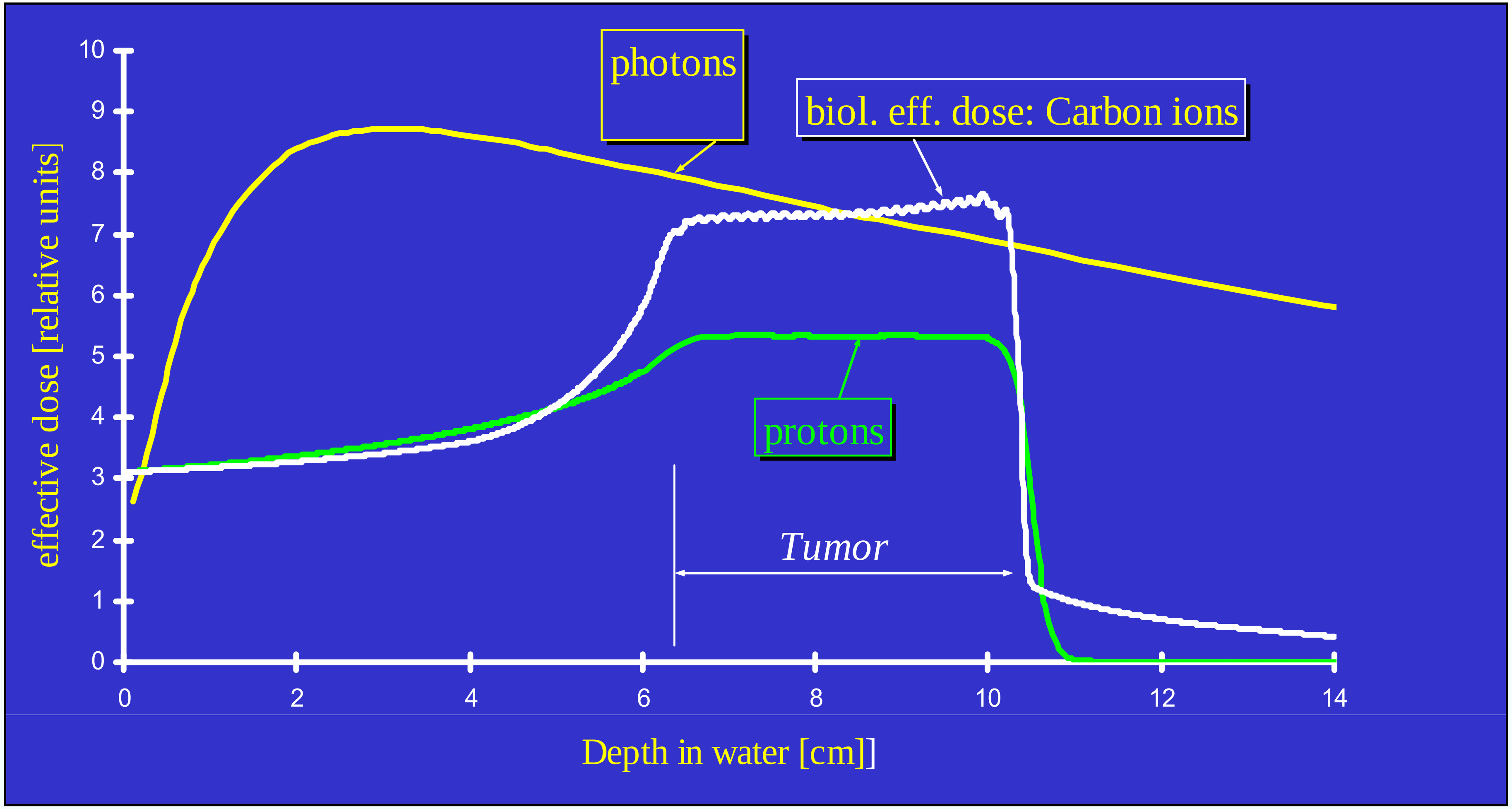
With Protons

(from Gillies McKenna)

"When proton therapy facilities become available it will become malpractice not to use them for children."

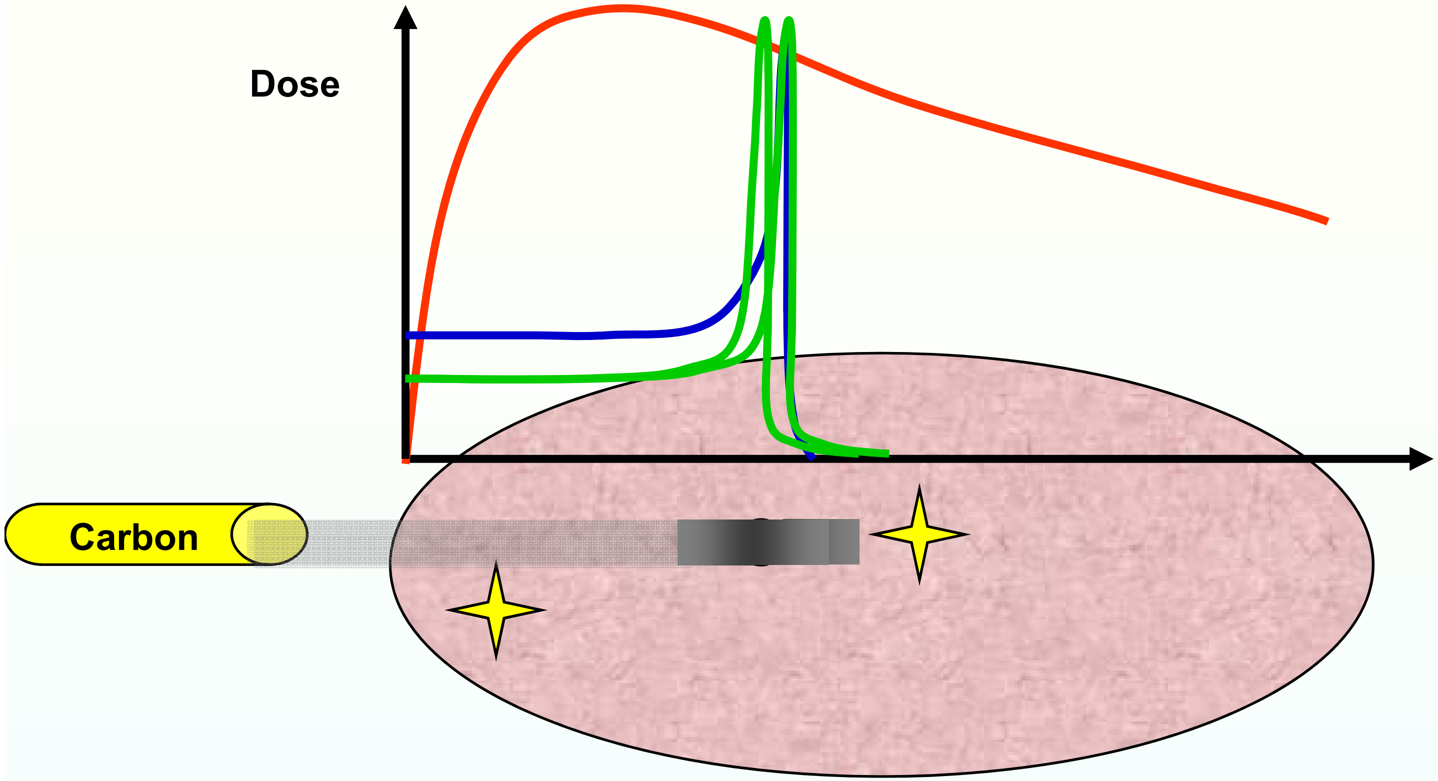
Herman Suit, M.D., D.Phil.
Chair, Radiation Medicine
Massachusetts General Hospital

Why use Carbon?

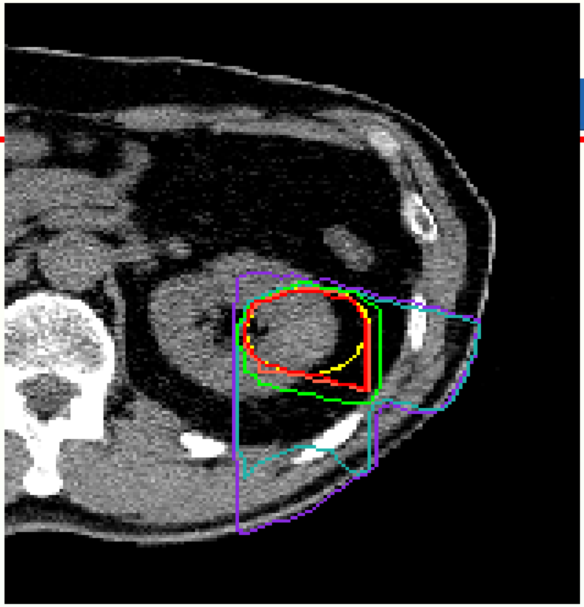


Daniela Schulz-Ertner, Heiddelberg

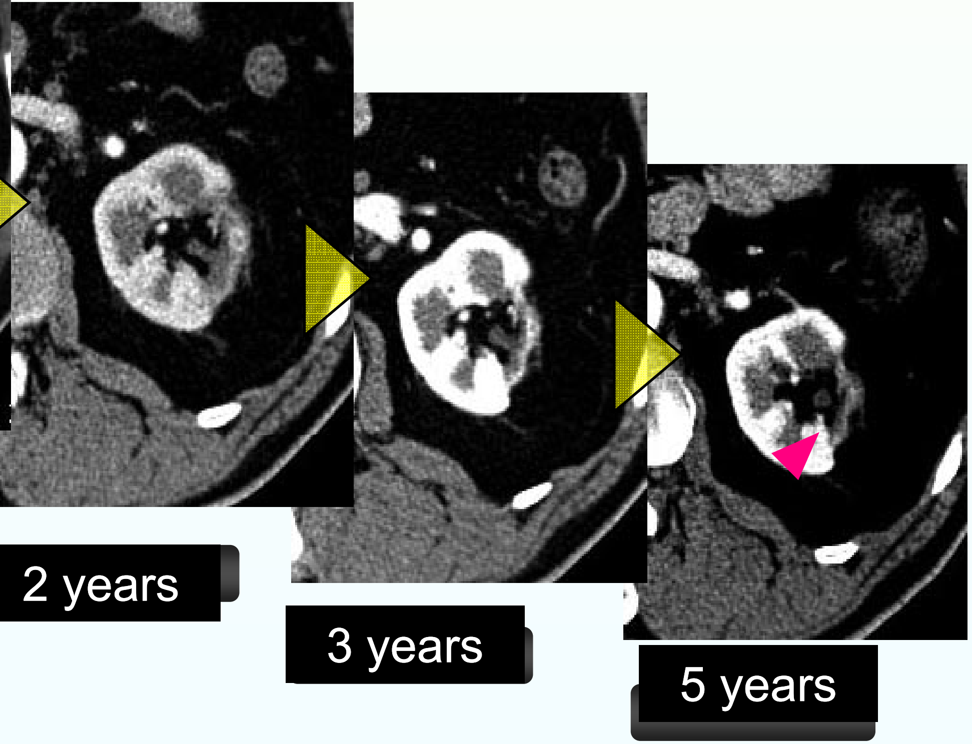
Can we do **even** better?



Does it work?

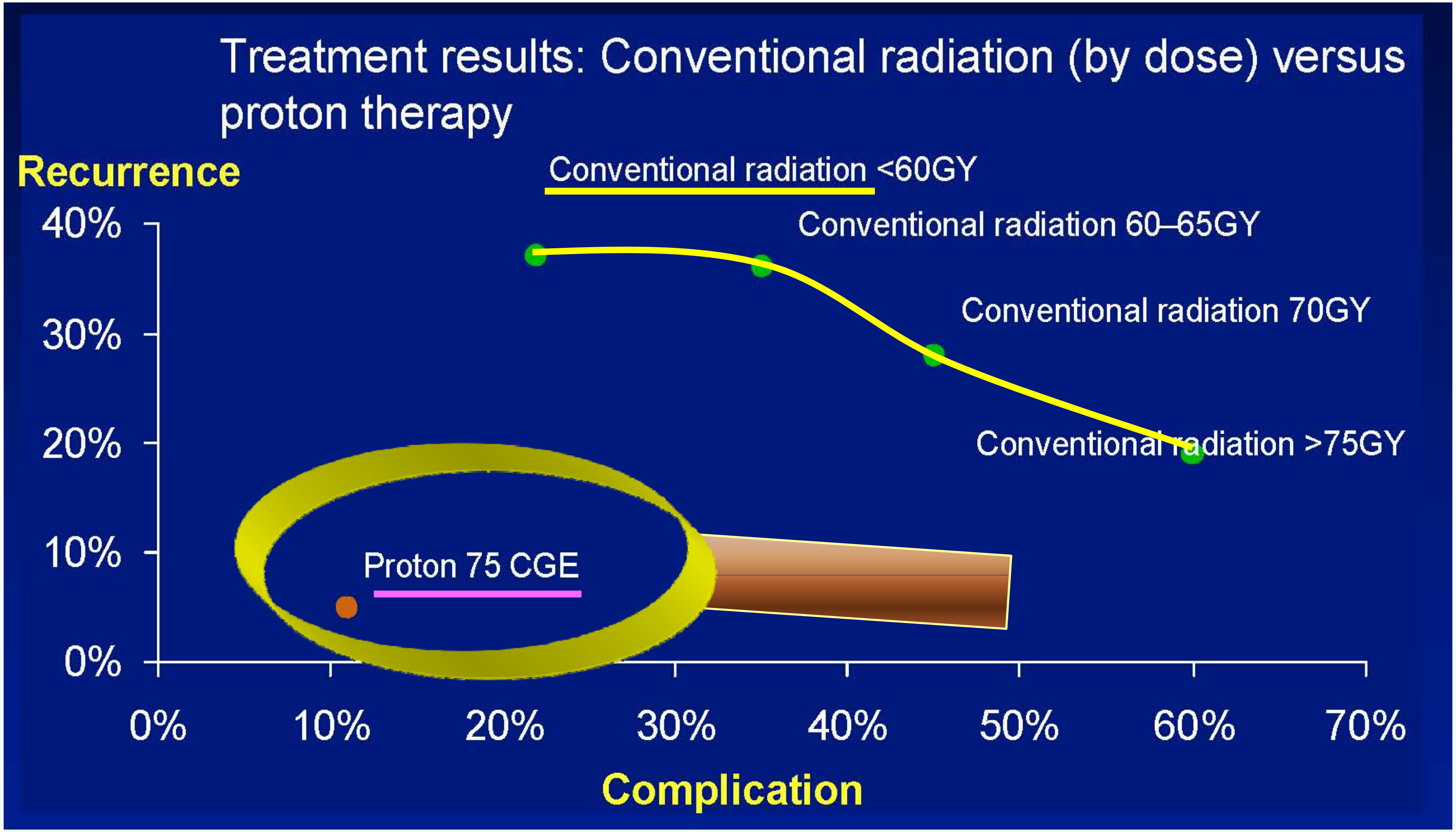


Cancer of the Kidney
Stage I: TIa N0 M0
80GyE / 16fr. /4wks



From Japan

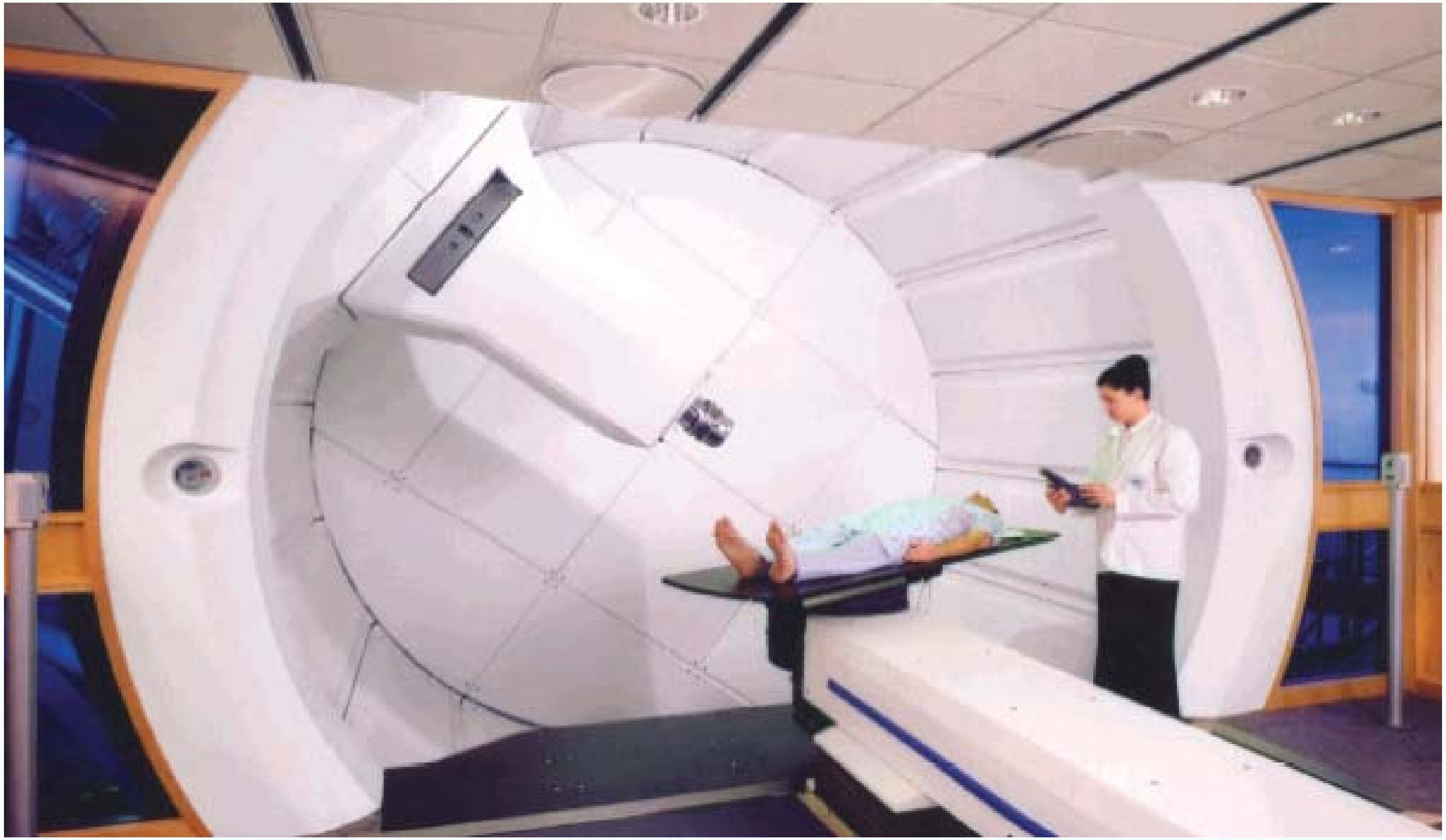
Prostate Cancer Results



Loma Linde

Japan: Tsukuba University
New Proton Medical Research Centre, 2001

A rotating gantry



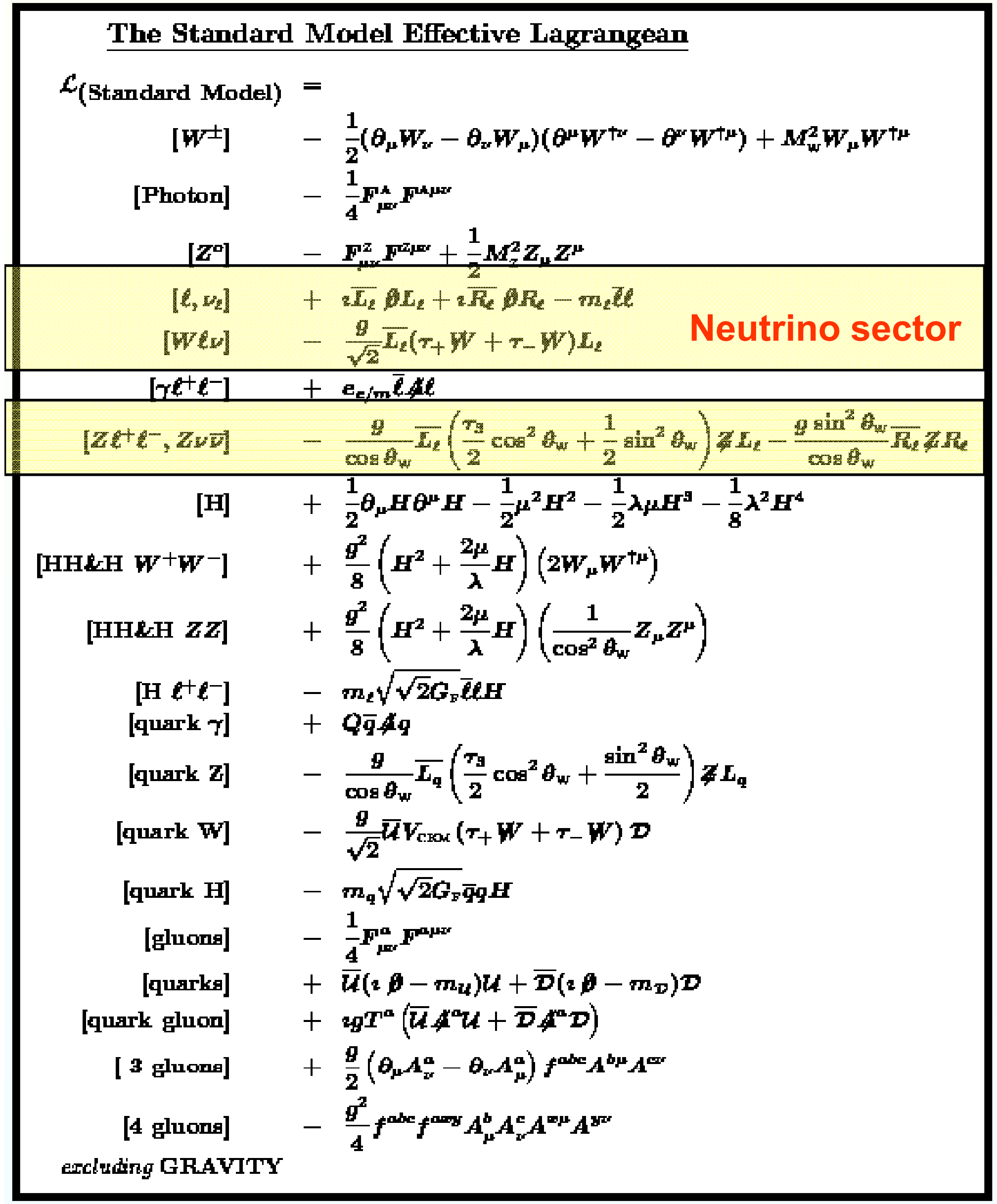
Neutrino Factory

The “ultimate” neutrino facility

http://www.adams-institute.ac.uk

Ken.Peach@adams-institute.ac.uk

The Standard Model



The Standard Model Effective Lagrangean

$\mathcal{L}_{(\text{Standard Model})} =$

[$W^\pm$] $-\frac{1}{2}(\partial_\mu W_\nu - \partial_\nu W_\mu)(\partial^\mu W^{\dagger\nu} - \partial^\nu W^{\dagger\mu}) + M_w^2 W_\mu W^{\dagger\mu}$

[Photon] $-\frac{1}{4}F^A_{\mu\nu}F^{A\mu\nu}$

[Z^o] $-F^Z_{\mu\nu}F^{Z\mu\nu} + \frac{1}{2}M_z^2 Z_\mu Z^\mu$

[ℓ, ν_ℓ] $+ i\overline{L_\ell}\,\not{\partial}L_\ell + i\overline{R_\ell}\,\not{\partial}R_\ell - m_\ell\bar{\ell}\ell$

[$W\ell\nu$] $-\frac{g}{\sqrt{2}}\overline{L_\ell}(\tau_+\not{W} + \tau_-\not{W})L_\ell$

Neutrino sector

[$\gamma\ell^+\ell^-$] $+ e_{e/m}\bar{\ell}\not{A}\ell$

[$Z\ell^+\ell^-, Z\nu\bar{\nu}$] $-\frac{g}{\cos\theta_w}\overline{L_\ell}\left(\frac{\tau_3}{2}\cos^2\theta_w + \frac{1}{2}\sin^2\theta_w\right)\not{Z}L_\ell - \frac{g\sin^2\theta_w}{\cos\theta_w}\overline{R_\ell}\not{Z}R_\ell$

[H] $+\frac{1}{2}\partial_\mu H\partial^\mu H - \frac{1}{2}\mu^2H^2 - \frac{1}{2}\lambda\mu H^3 - \frac{1}{8}\lambda^2H^4$

[HH&H W^+W^-] $+\frac{g^2}{8}\left(H^2 + \frac{2\mu}{\lambda}H\right)\left(2W_\mu W^{\dagger\mu}\right)$

[HH&H ZZ] $+\frac{g^2}{8}\left(H^2 + \frac{2\mu}{\lambda}H\right)\left(\frac{1}{\cos^2\theta_w}Z_\mu Z^\mu\right)$

[H $\ell^+\ell^-$] $-m_\ell\sqrt{\sqrt{2}G_F}\bar{\ell}\ell H$

[quark γ] $+Q\bar{q}\not{A}q$

[quark Z] $-\frac{g}{\cos\theta_w}\overline{L_q}\left(\frac{\tau_3}{2}\cos^2\theta_w + \frac{\sin^2\theta_w}{2}\right)\not{Z}L_q$

[quark W] $-\frac{g}{\sqrt{2}}\overline{\mathcal{U}}V_{\text{CKM}}(\tau_+\not{W} + \tau_-\not{W})\mathcal{D}$

[quark H] $-m_q\sqrt{\sqrt{2}G_F}\bar{q}qH$

[gluons] $-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$

[quarks] $+\overline{\mathcal{U}}(i\not{\partial} - m_{\mathcal{U}})\mathcal{U} + \overline{\mathcal{D}}(i\not{\partial} - m_{\mathcal{D}})\mathcal{D}$

[quark gluon] $+igT^a\left(\overline{\mathcal{U}}\not{A}^a\mathcal{U} + \overline{\mathcal{D}}\not{A}^a\mathcal{D}\right)$

[3 gluons] $+\frac{g}{2}\left(\partial_\mu A^a_\nu - \partial_\nu A^a_\mu\right)f^{abc}A^{b\mu}A^{c\nu}$

[4 gluons] $-\frac{g^2}{4}f^{abc}f^{a\alpha\beta}A^b_\mu A^c_\nu A^{\alpha\mu}A^{\beta\nu}$

excluding GRAVITY

The Parameters

- 6 quark masses
  - m_u , m_c, m_t
  - m_d, m_s, m_b
- 3 lepton masses
  - m_e, m_μ, m_τ
- 2 vector boson masses
  - M_w, M_Z
    - (m_γ, m_g=0)
- 1 Higgs mass
  - M_h
- 3 coupling constants
  - G_F, α, α_s
- 3 quark mixing angles
  - θ_{12}, θ_{23}, θ_{13}
- 1 quark phase
  - δ

Neutrino masses identically 0!!!!

Neutrino Mixing

Atmospheric **3G** **solar** **Majorana**

$$U_{MNS}=\begin{bmatrix}1&&\\&c_{23}&s_{23}\\&-s_{23}&c_{23}\end{bmatrix}\otimes\begin{bmatrix}c_{13}&&s_{13}e^{-i\delta}\\&1&\\-s_{13}e^{i\delta}&&c_{13}\end{bmatrix}\otimes\begin{bmatrix}c_{12}&s_{12}&\\-s_{12}&c_{12}&\\&&1\end{bmatrix}\otimes\begin{bmatrix}1&&\\&e^{i\alpha}&\\&&e^{i\beta}\end{bmatrix}$$

$$=\begin{bmatrix}c_{12}c_{13}&s_{12}c_{13}&s_{13}e^{i\delta}\\-c_{23}s_{12}-s_{13}s_{23}c_{12}e^{i\delta}&c_{23}c_{12}-s_{13}s_{23}s_{12}e^{i\delta}&c_{13}s_{23}\\s_{23}s_{12}-s_{13}c_{23}c_{12}e^{i\delta}&-s_{23}c_{12}-s_{13}c_{23}s_{12}e^{i\delta}&c_{13}c_{23}\end{bmatrix}\otimes\begin{bmatrix}1&&\\&e^{i\alpha}&\\&&e^{i\beta}\end{bmatrix}$$

$$\left|\Delta m^2_{32}\right|=(2.38\pm0.27)\times10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{23}=0.45^{+0.16}_{-0.09}$$

$$\Delta m^2_{21}=(7.66\pm0.35)\times10^{-5}\,\mathrm{eV}^2$$

$$\sin^2\theta_{12}=0.326^{+0.04}_{-0.05}$$

$$\sin^2\theta_{13}<0.032$$

$Sign\left(\Delta m^2_{32}\right)$ unknown

δ,α,β unknown

masses $<$ O(1eV)

2s

Fogli et al, 2008

Parameters of neutrino oscillation

$c_{ij}=\cos\theta_{ij}$

$s_{ij}=\sin\theta_{ij}$

1 absolute mass scale	m_{ν_e}
2 squared mass diffs	Δm^2_{12} , Δm^2_{23}
3 mixing angles	θ_{12} , θ_{23} , θ_{13}
1 phase	δ (always $\sin\theta_{13}e^{i\delta}$)
2 Majorana phases	α,β

$$\begin{cases}\Delta m^2_{ji}=m^2_j-m^2_i\\ \Delta m^2_{31}=\Delta m^2_{32}+\Delta m^2_{21}\end{cases}$$

Why is it hard to measure the parameters?

$$P\left(\nu_\mu \Rightarrow \nu_e\right) = \quad 4c_{13}^2 s_{12}^2 \left(c_{12}^2 c_{23}^2\right)\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$4c_{13}^2 s_{12}^2 \left(c_{12}^2 c_{23}^2 - s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\boxed{\cos\delta}\right)\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$+8c_{13}^2 s_{12}s_{13}s_{23}\left(c_{12}c_{23}\boxed{\cos\delta} - s_{12}s_{13}s_{23}\right)\cos\left(\frac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$+4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)\left(1+\left(1-2s_{13}^2\right)\frac{2a}{\Delta m_{31}^2}\right)$$

$$\nu_\mu \Rightarrow \bar{\nu}_\mu \quad \Leftrightarrow \quad a \Rightarrow -a$$

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\left(\frac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$-8c_{13}^2 s_{13}^2 s_{23}^2 \cos\left(\frac{\Delta m_{32}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)\left(1-2s_{13}^2\right)\frac{aL}{4E}$$

a =2□2 $G_F n_e E_n$ = 7.6 10^{-5} r E

Where is the electron density ; r is the density (g/cm^3) ;   E is the neutrino energy (GeV)

c_{ij}=cosq$_{ij}$, s_{ij}=sinq$_{ij}$

(Richter: hep-ph/0008222)

What to Measure?

Neutrinos

ν_e disappearance

$\nu_e \rightarrow \nu_\mu$ appearance

$\nu_e \rightarrow \nu_\tau$ appearance

ν_μ disappearance

$\nu_\mu \rightarrow \nu_e$ appearance

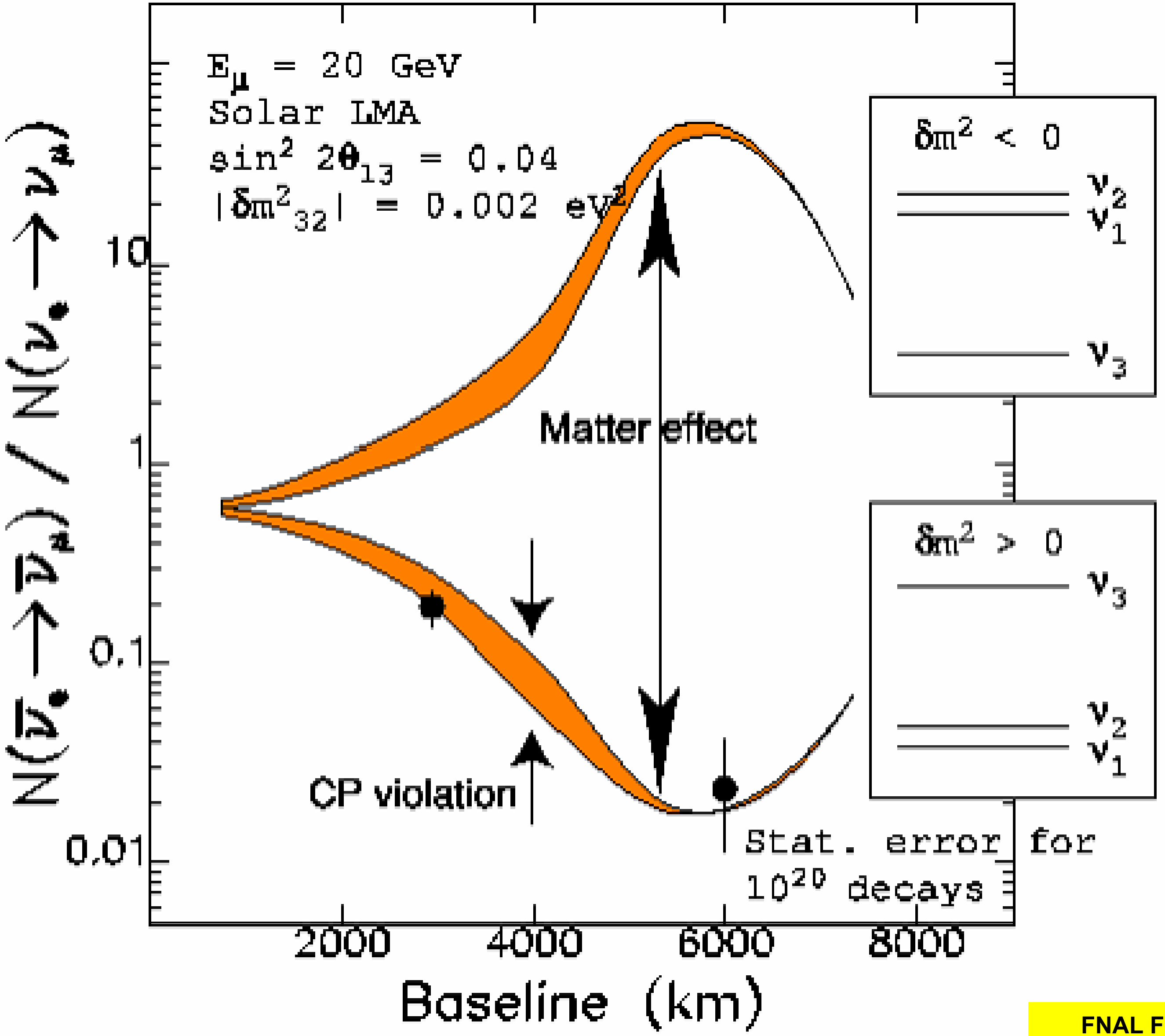
$\nu_\mu \rightarrow \nu_\tau$ appearance

… and the corresponding antineutrino interactions

Note: the beam requirements for these experiments are:

high intensity	known flux
known spectrum	known composition (preferably no background)

CP-violation



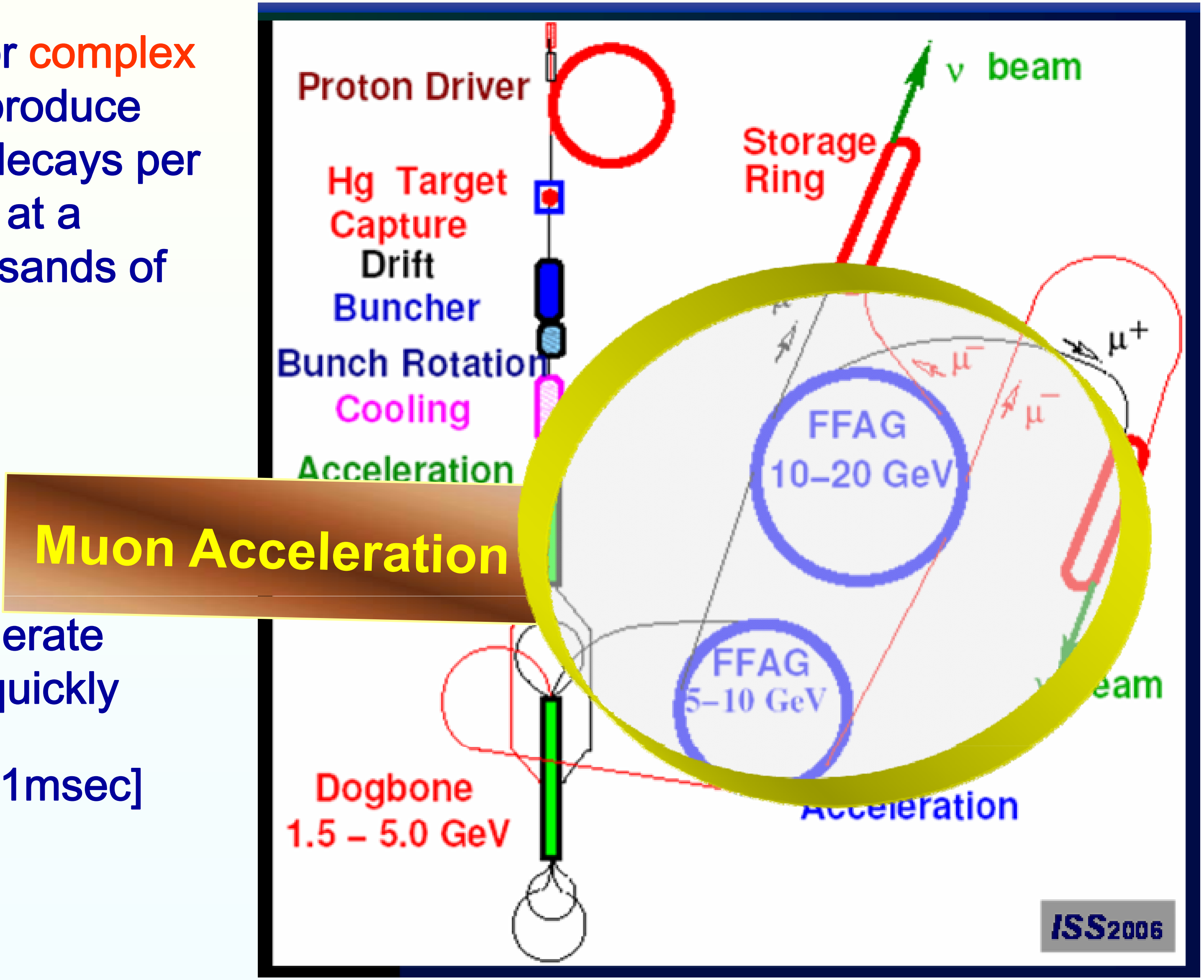
FNAL Feasibality Study 1

A Neutrino Factory is …

… an accelerator complex designed to produce $>10^{20}$ muon decays per year directed at a detector thousands of km away

… need to accelerate muons very quickly

[@5 GeV, t_m~0.1msec]



The non-scaling FFAG Accelerator

Fixed-Field Alternating Gradient

Classical Accelerator Types

Type	Magnetic Field	RF	Radius
Betatron	Variable	✗	Fixed
Cyclotron	Fixed	✓	Variable
Synchrotron	Variable	✓	Fixed
FFAG	Fixed	✓	~Fixed
Linear accelerators (Linacs)	✗	✓	∞

+ assorted others – electrostatic, RFQs etc …

+ new ideas (laser-plasma for example) …

Fixed Field Alternating Gradient accelerators

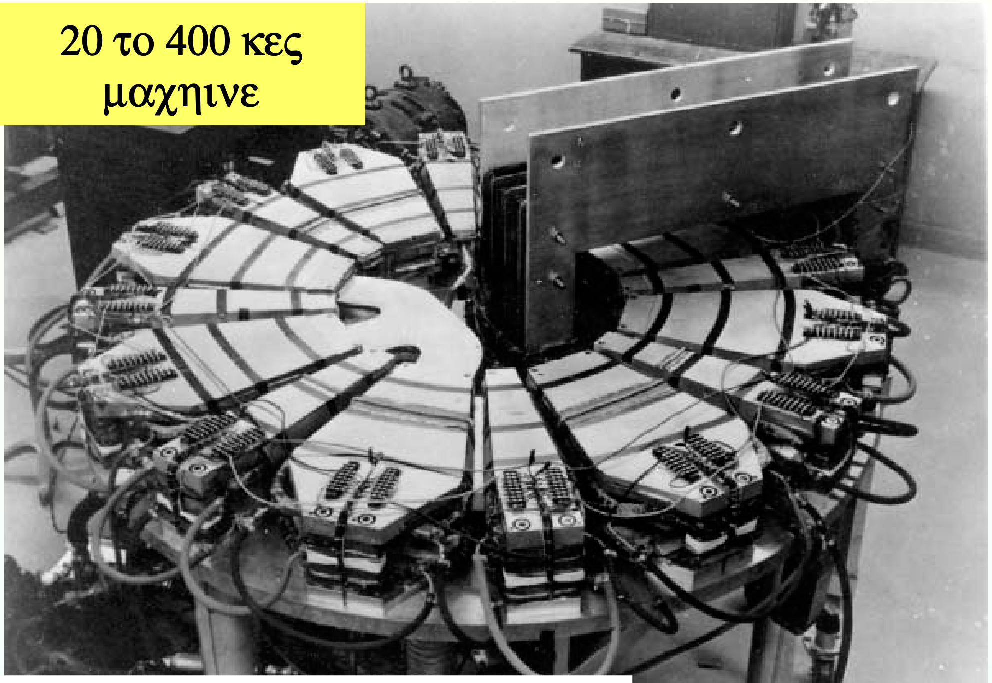
Type	Magnetic Field	RF	Radius
FFAG	Fixed	✓	~Fixed

- **Fixed-Field** (like a cyclotron)
  - Rapid acceleration possible
  - Rapid cycling possible
- **Alternating Gradient** (like a synchrotron)
  - Focussing!!!!
    - Small(er) magnets/beam pipe/vacuum system
- **… and large acceptance**
- **The best of both worlds!**
  - So why is the world not full of FFAGs?

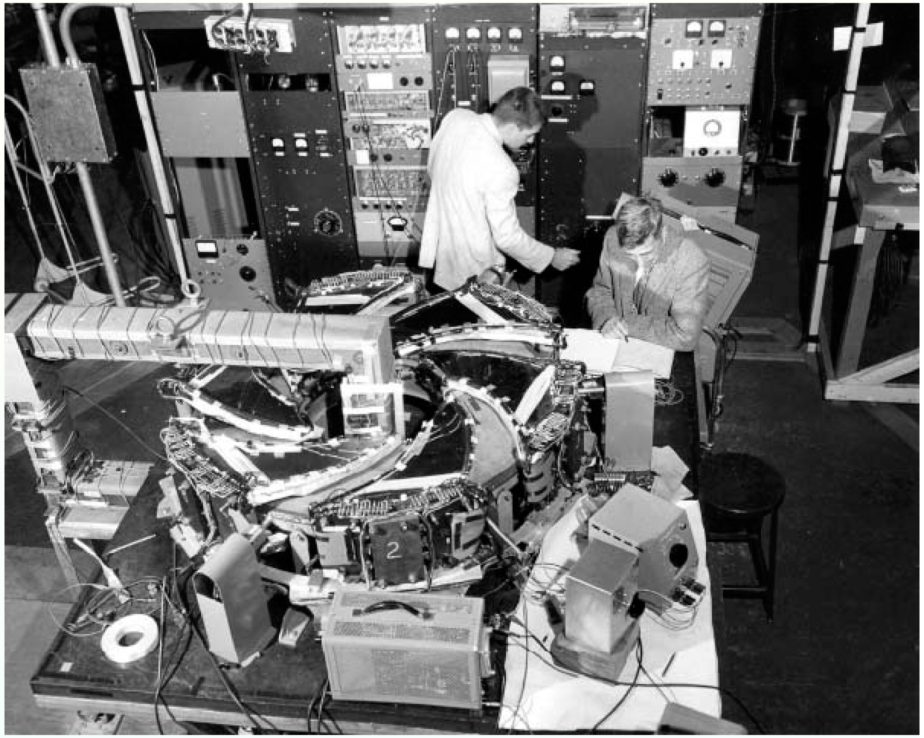
Early FFAGs (1955-1960)

- **MURA built several *electron* FFAGs in the 1950s**

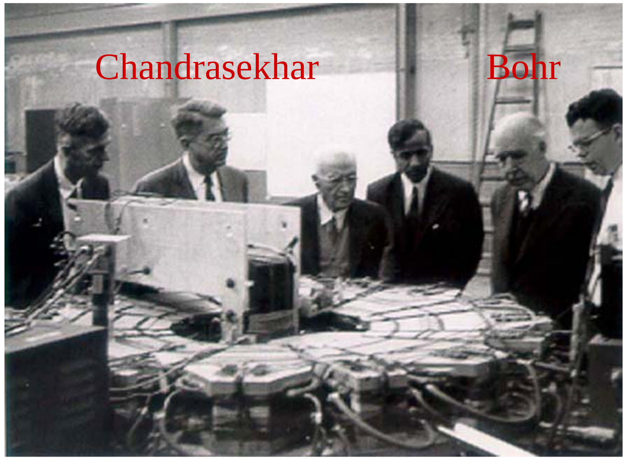
20 το 400 κες
μαχηινε



Radial sector



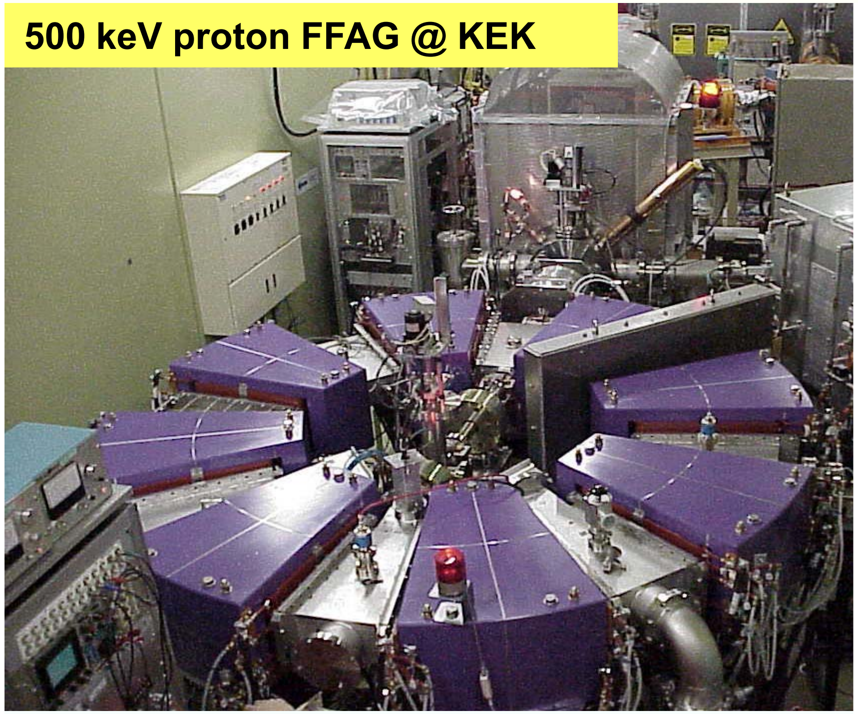
Spiral sector



Large complicated magnets

- **c.f. Cyclotron – large simple magnets**
- **c.f. Synchrotron – small simple magnets**

Newer FFAG's (post-2000)


500 keV proton FFAG @ KEK


150 MeV proton FFAG @ KEK

- The Japanese have built two "proof of principle" proton FFAGs

… but …

… the magnets are LARGE and COMPLICATED

- **Why?**

Orbit excursion ~ 0.9m

$$B = B_0 \left(\frac{r}{r_0} \right)^k$$

where $k >> 1$

$$p \propto r^{k+1}$$

- **Why does *k* have to be so large?**
  1. **Larger *k* means stronger focussing**
  2. ***k* > 0 means horizontal focussing**
     - **This means that the average field increases with radius**
  3. **The momentum compaction** a ≈ *1/(k+1)*
     - **Large momentum bite ➔ small orbit excursion**

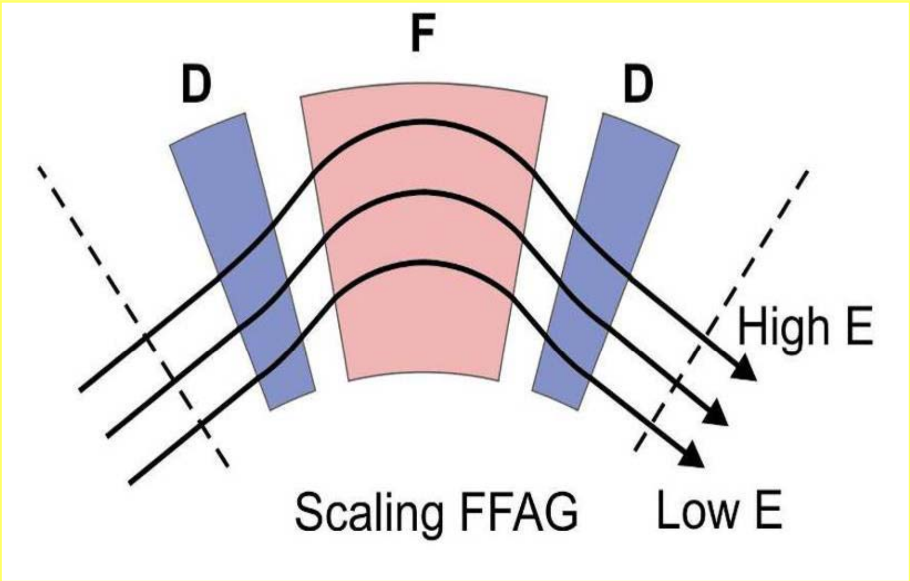
$$\alpha = \frac{\partial R}{R} \bigg/ \frac{\partial p}{p}$$

Scaling and non-scaling FFAGs

$$B = B_0 \left(\frac{r}{r_0} \right)^k$$

where *k >> 1*

$$p \propto r^{k+1}$$



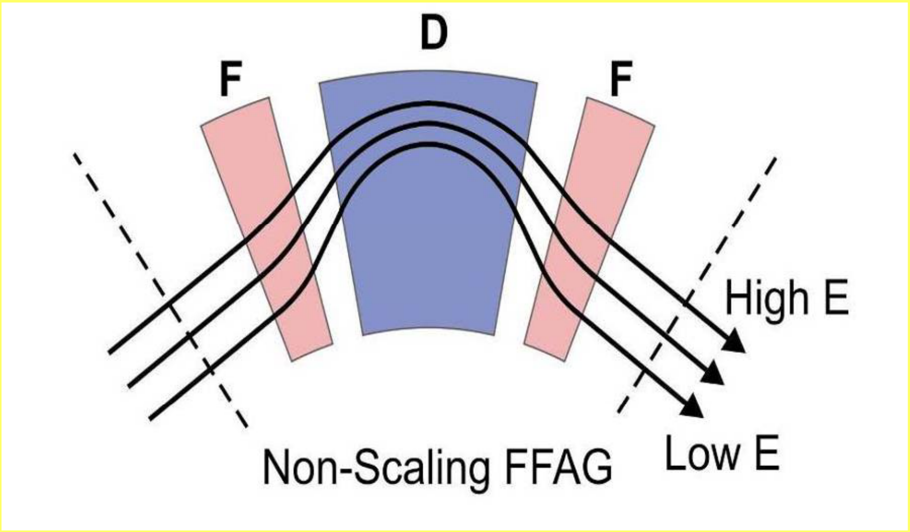
Invented in 1999

$$B = B_0 \left(\frac{r}{r_0} \right)^k$$

where *k = 1*

Linear magnets!

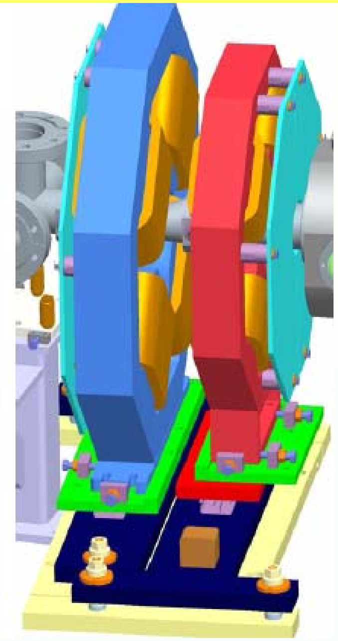
i.e. quadrupoles

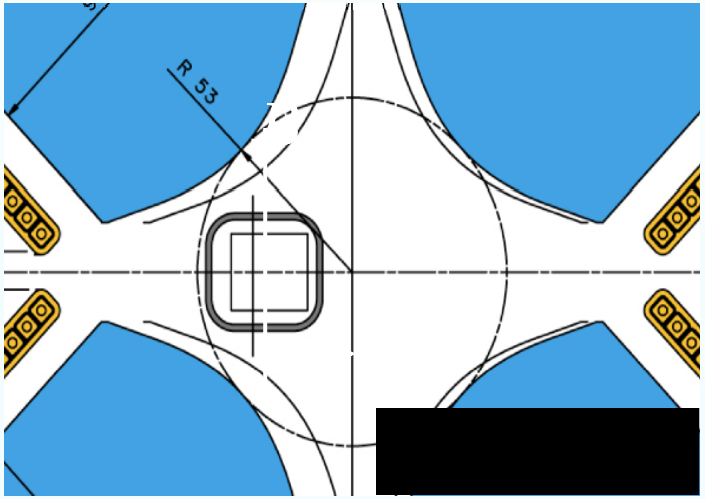


Simpler Magnets

… the magnets are LARGE and COMPLICATED

to magnets that are SMALL and SIMPLE





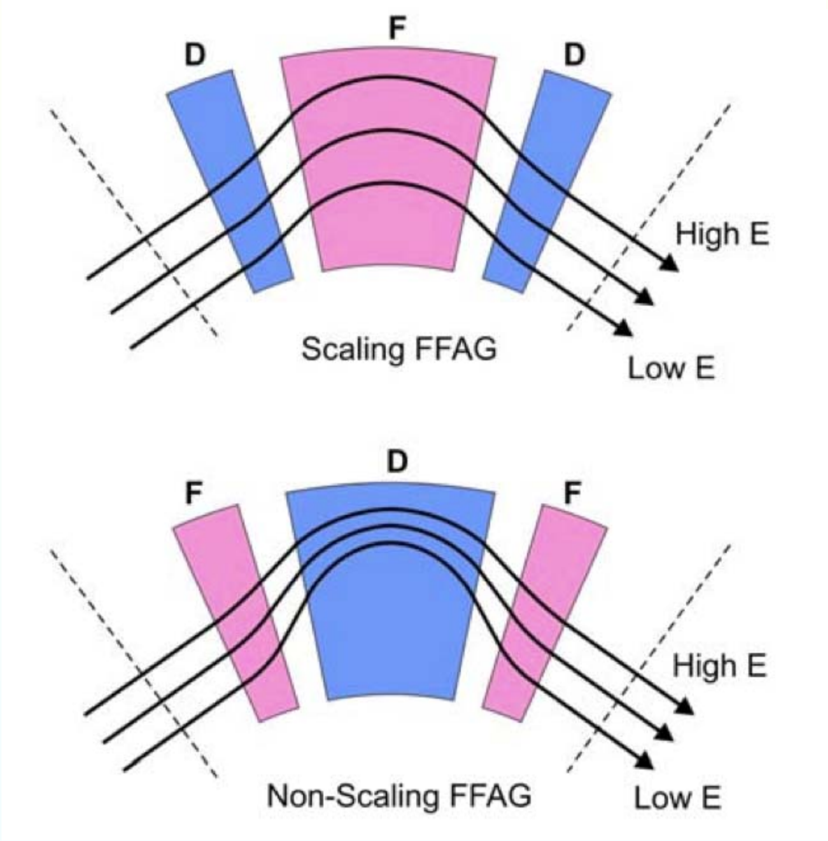
[redacted]

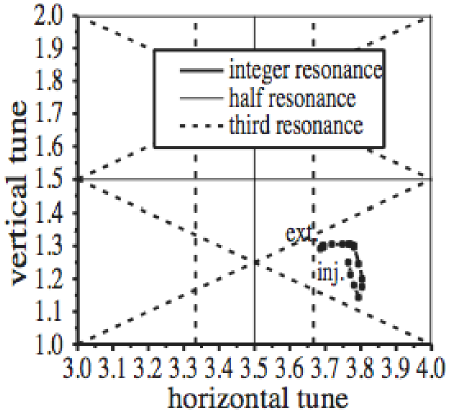
The ns-FFAG

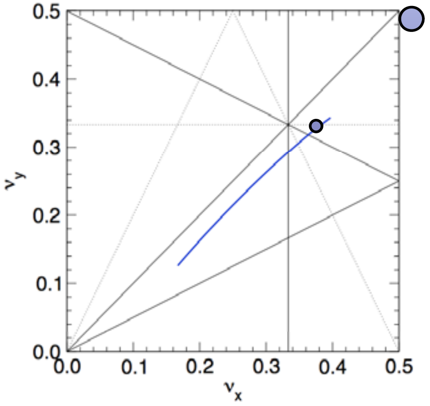
- ***Should*** **combine the advantages of FFAGs**
  - **Fixed Field**
    - **Fast cycling (limited essentially by RF)**
    - **Simpler, cheaper power supplies**
    - **No eddy-currents**
    - **High intensity (pulsed, ~continuous)**
    - **Low beam losses**
    - **Easier maintenance and operation**
    - **Lower stresses**
  - **Strong Focussing**
    - **Magnetic ring**
    - **Variable energy extraction**
    - **Higher energies (than cyclotrons)**
    - **Different ion species possible**
- **with relative ease of construction**

… so … where is the catch?

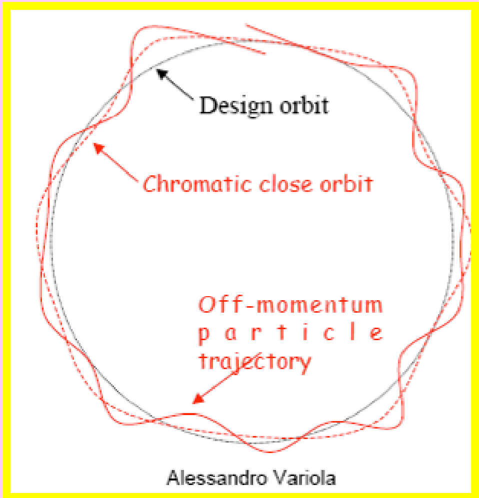
- **Variable tune!**







Must cross resonances

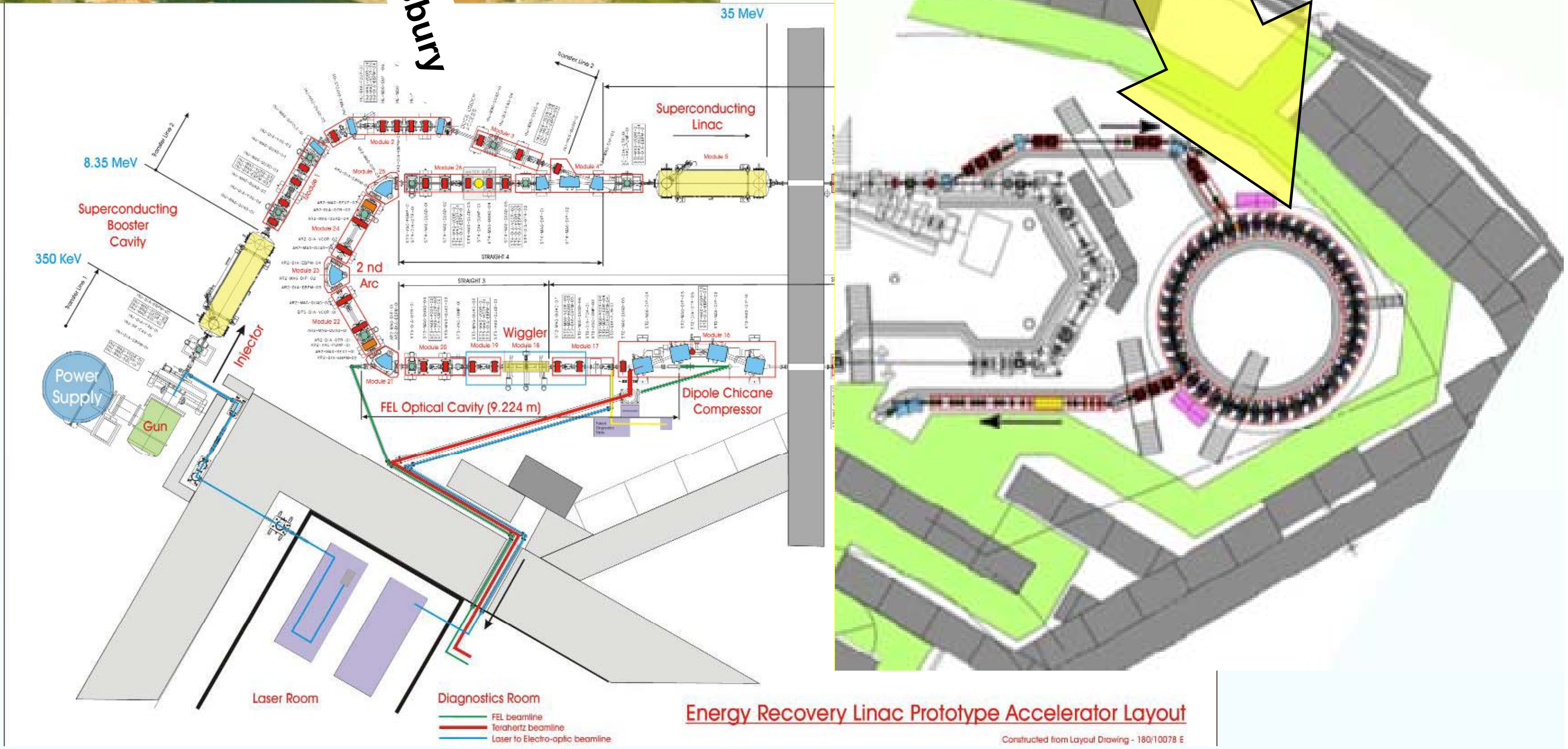


Tune ~ w_b/w_c

Does it work?

- We do not know!
  - There is no “no-go” theorem
- Need for a “proof of principle” demonstrator
  - EMMA
    - Electron Model for Many Applications
      - Originally Electron Model for Muon Acceleration
- Funding obtained in the UK to design and build a EMMA – the world’s first non-scaling FFAG accelerator!

Location of EMMA

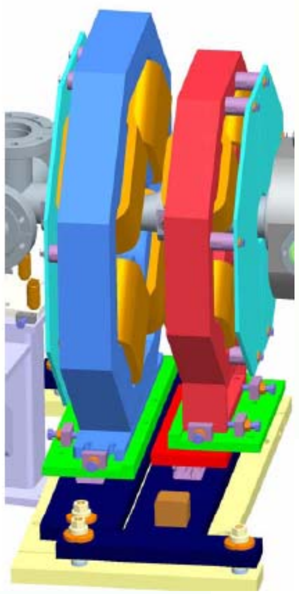


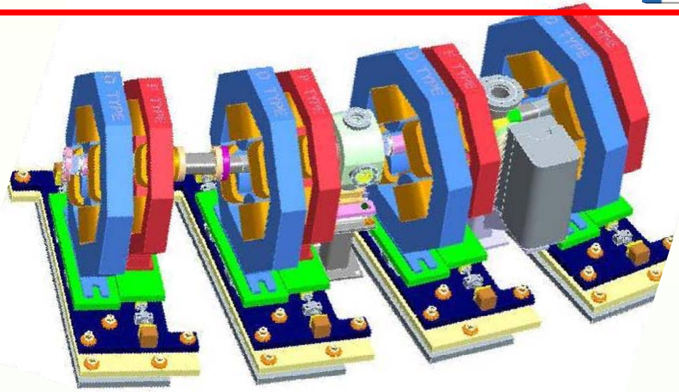
Energy Recovery Linac Prototype Accelerator Layout

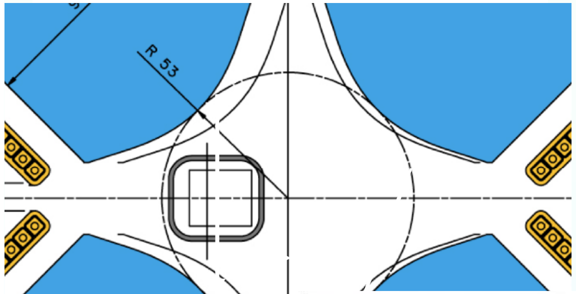
Constructed from Layout Drawing - 180/10078 E

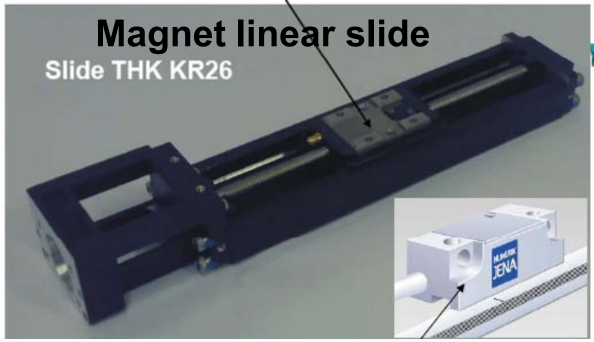
EMMA: Lattice & Magnets

Magnet Type	Units	QD	QF
Quantity		42	42
Inscribed radii	mm	51.0	36.0
Good gradient region	mm	-56.0, -9.9	+15.8, -32.0
Good gradient quality	%	± 0.1	± 0.1
Gradient strength (standard)	T	0.367	0.403
Gradient strength (max)	T	0.440	0.483
Translation	mm	+14.5 -5.3	+2.7 -2.6

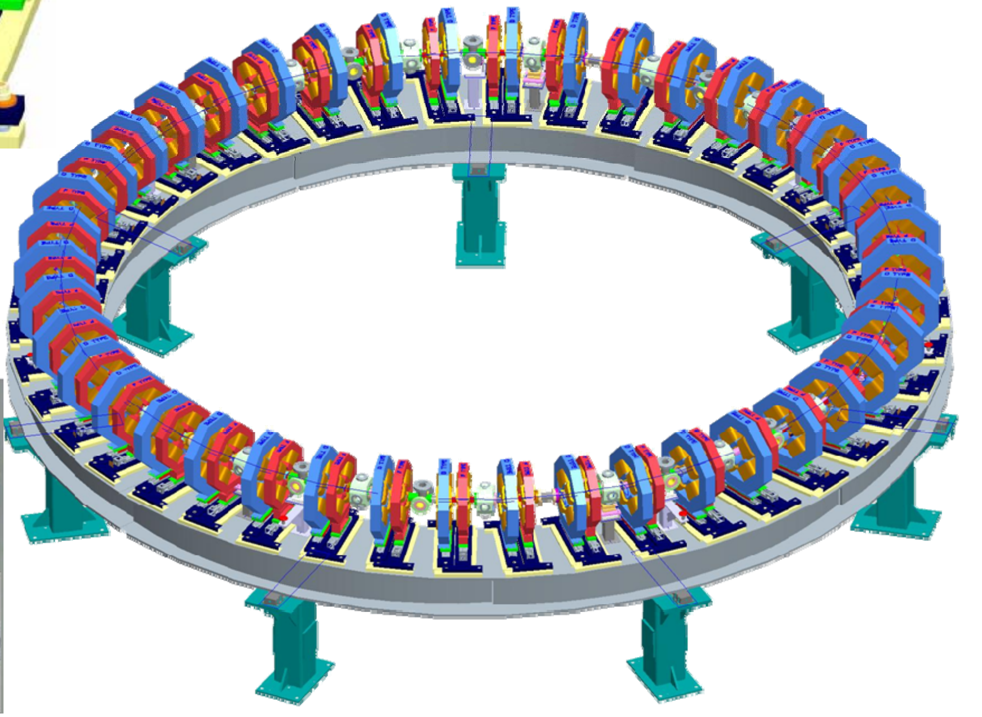







Magnet linear slide

Slide THK KR26



After Neil Bliss

EMMA Parameters

42 identical straight length 394.481 mm

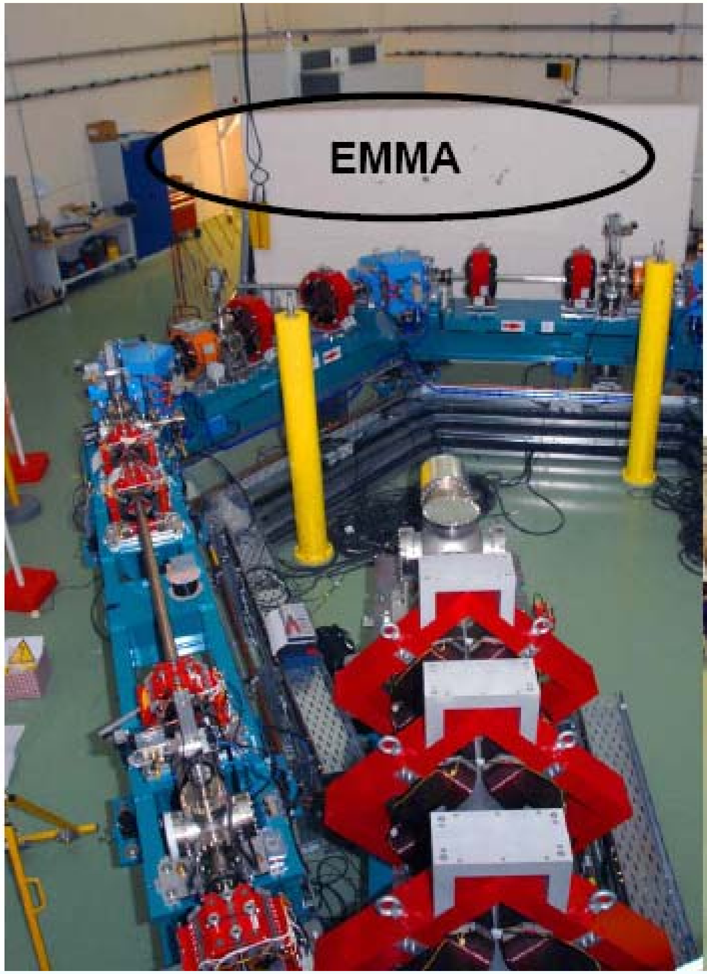
Long drift	210.000 mm
F Quad	58.782 mm
Short drift	50.000 mm
D Quad	75.699 mm

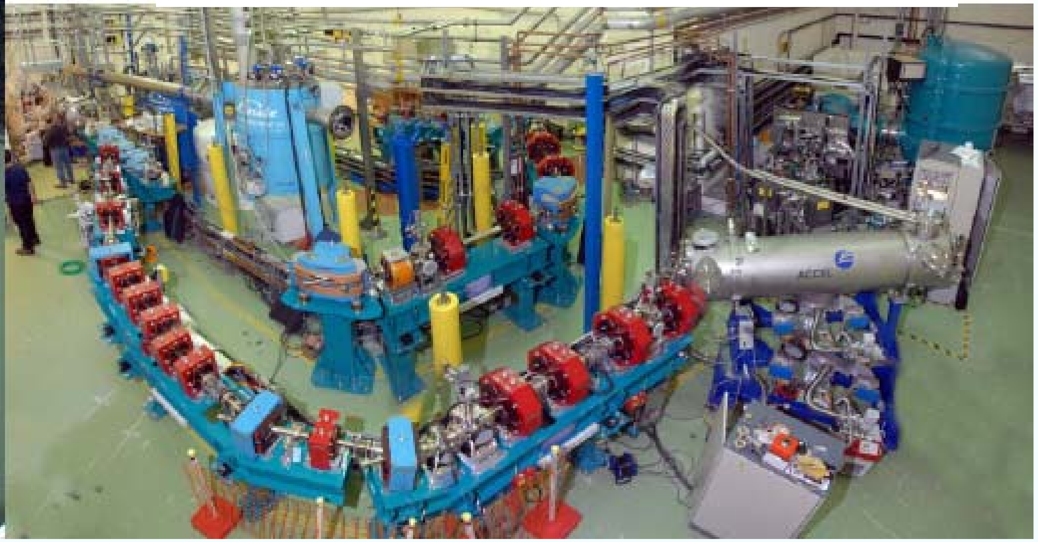
Parameter	**Value**
Kinetic Energy range	10 – 20 MeV
Injection	10 – 20 MeV
Number of cells	42
Lattice	F/D Doublet
Cell length	394.481 mm
Circumference	16568.202 mm
Average beam current	13 μA
Injected emittance	5-20 mm mrad (norm.)
Model acceptance	3000 mm mrad (norm.)
Orbit swing	3 cm
Bunch charge	16-32 pC single bunch 1 – 2 E8
Repetition rate	1, 5, 20 Hz
RF Frequency	1.3 GHz
RF Frequency range	(1.295981 to 1.301554)
RF voltage	20 – 120 kV/cavity
Number of RF cavities	19

EMMA at the ALICE@Daresbury

ALICE Parameters

Parameter	Value
Nominal Gun Energy	350 keV
Max. Booster Volts	8 MV
TL 2 Energy	8.33 MeV
Max. Linac Volts	26.67 MV
Max. Energy	35 MeV
Linac RF Frequency	1.300 GHz (+/- 1 MHz)
Bunch Repetition Rate	81.25 MHz
Bunch Spacing	12.3 ns
Max Bunch Charge	80 pC
Particles per Bunch	5 x 10^8





After Neil Bliss

Status of EMMA

- Funded! (~£6M)
  - Started 1st April 2007
- Lattice - fixed
- Component design - ongoing
  - Prototype quads being measured now
- Final design - complete Jan 08
- Construction - complete Jul 09
- Beam studies - until Sep 10
  - At least …

After Tkeichiro Yokoi

British Accelerator Science
&
Radiation Oncology Consortium

PAMELA

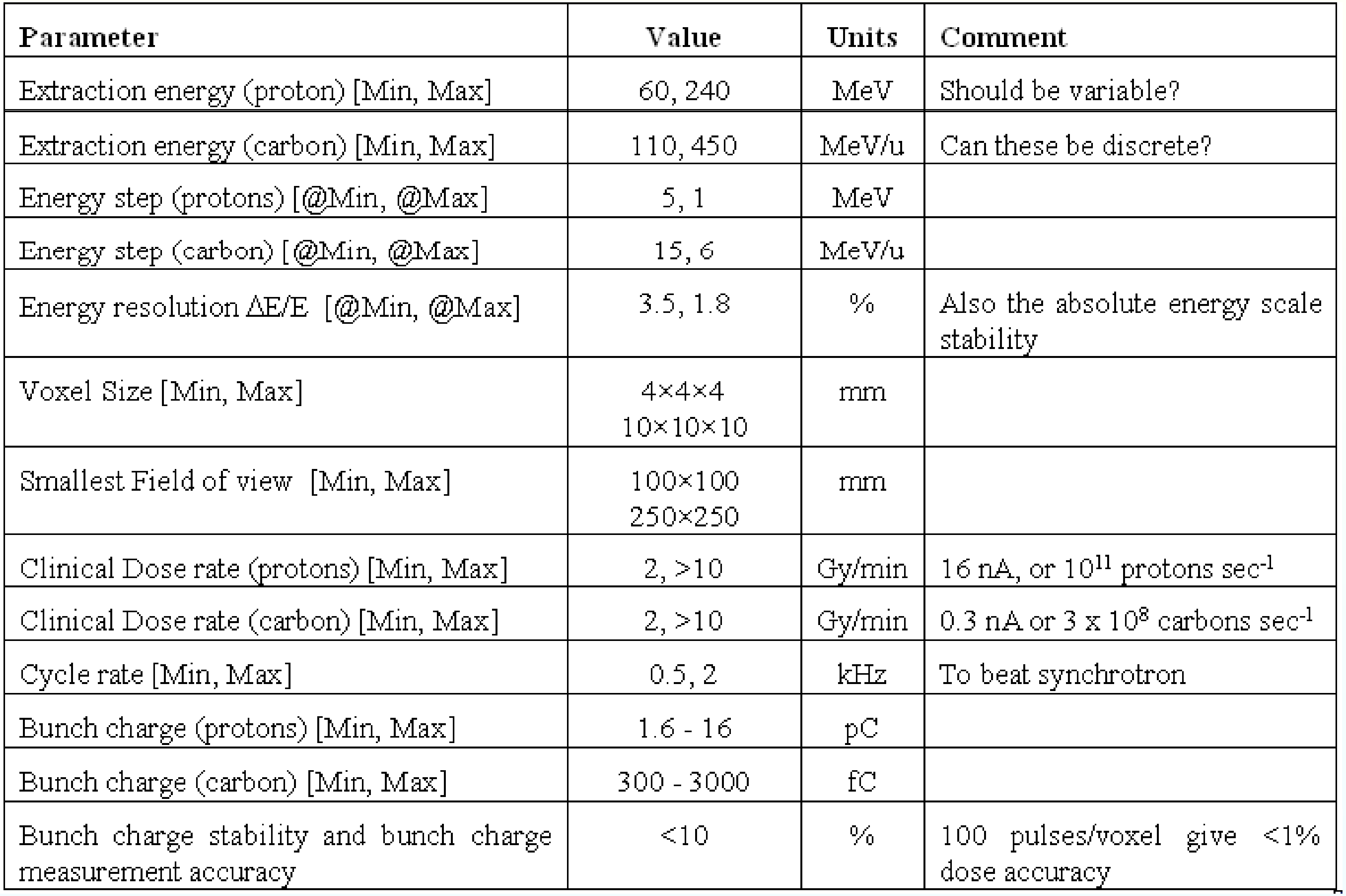
Charged Particle Therapy (CPT)
BASROC & CONFORM

http://www.adams-institute.ac.uk http://www.basroc.org.uk Ken.Peach@adams-institute.ac.uk

The requirements

- There are obvious potential benefits from proton/light ion therapy
  - Need to maximise the benefits
- Requirements
  - Rapid variable energy extraction
  - Rapid variable transverse spot scanning
  - Variable ion species
  - Accurate dose measurements
    - Flux control

Clinical Requirements



Parameter	**Value**	**Units**	**Comment**
Extraction energy (proton) [Min, Max]	60, 240	MeV	Should be variable?
Extraction energy (carbon) [Min, Max]	110, 450	MeV/u	Can these be discrete?
Energy step (protons) [@Min, @Max]	5, 1	MeV	
Energy step (carbon) [@Min, @Max]	15, 6	MeV/u	
Energy resolution ΔE/E [@Min, @Max]	3.5, 1.8	%	Also the absolute energy scale stability
Voxel Size [Min, Max]	4×4×4 10×10×10	mm	
Smallest Field of view [Min, Max]	100×100 250×250	mm	
Clinical Dose rate (protons) [Min, Max]	2, >10	Gy/min	16 nA, or 10^{11} protons sec^{-1}
Clinical Dose rate (carbon) [Min, Max]	2, >10	Gy/min	0.3 nA or 3×10^{8} carbons sec^{-1}
Cycle rate [Min, Max]	0.5, 2	kHz	To beat synchrotron
Bunch charge (protons) [Min, Max]	1.6 - 16	pC	
Bunch charge (carbon) [Min, Max]	300 - 3000	fC	
Bunch charge stability and bunch charge measurement accuracy	<10	%	100 pulses/voxel give <1% dose accuracy

PAMELA Objectives

- **Produce the conceptual design for a combined proton/carbon/light ion cancer therapy facility**
  - **250 MeV protons, 400 MeV/u Carbon**
- **Preliminary performance parameters**
  - **>100 Hz cycle rate and one turn ejection**
  - **Dose rate of 2 to 10 Gy/minute.**
    - **(1Gy ~ 2 x 10^{10} protons)**
  - **Voxel size from 4x4x4 mm^3 to 10x10x10 mm^3**
  - **Up to 100 pulses/voxel**
    - **With a typical tumour volume of 250 cm^3 & voxel-volume 0.064 cm3 (4x4x4), there are 4,000 elements, which with 10 to 100 pulses for each voxel needs 40k to 400k pulses in around 300 seconds, or a cycle rate of 133 Hz to 1.3 kHz.**

Accelerator Technology?

- **4 possible technologies**
  - **Cyclotrons**
    - **Fixed energy extraction, difficult for Carbon at full energy (equivalent to 1.2 GeV/c protons)**
  - **Synchrotrons**
    - **Flexible, but difficult to meet the pulse requirements; slow extraction difficult; normal conducting machine (stability?)**
  - **(ns) FFAG**
    - **Flexible, rapid cycling (fixed field), variable energy … but … unproven technology**
  - **Laser-Plasma Ion accelerators**
    - **Far in the future …**

Challenges

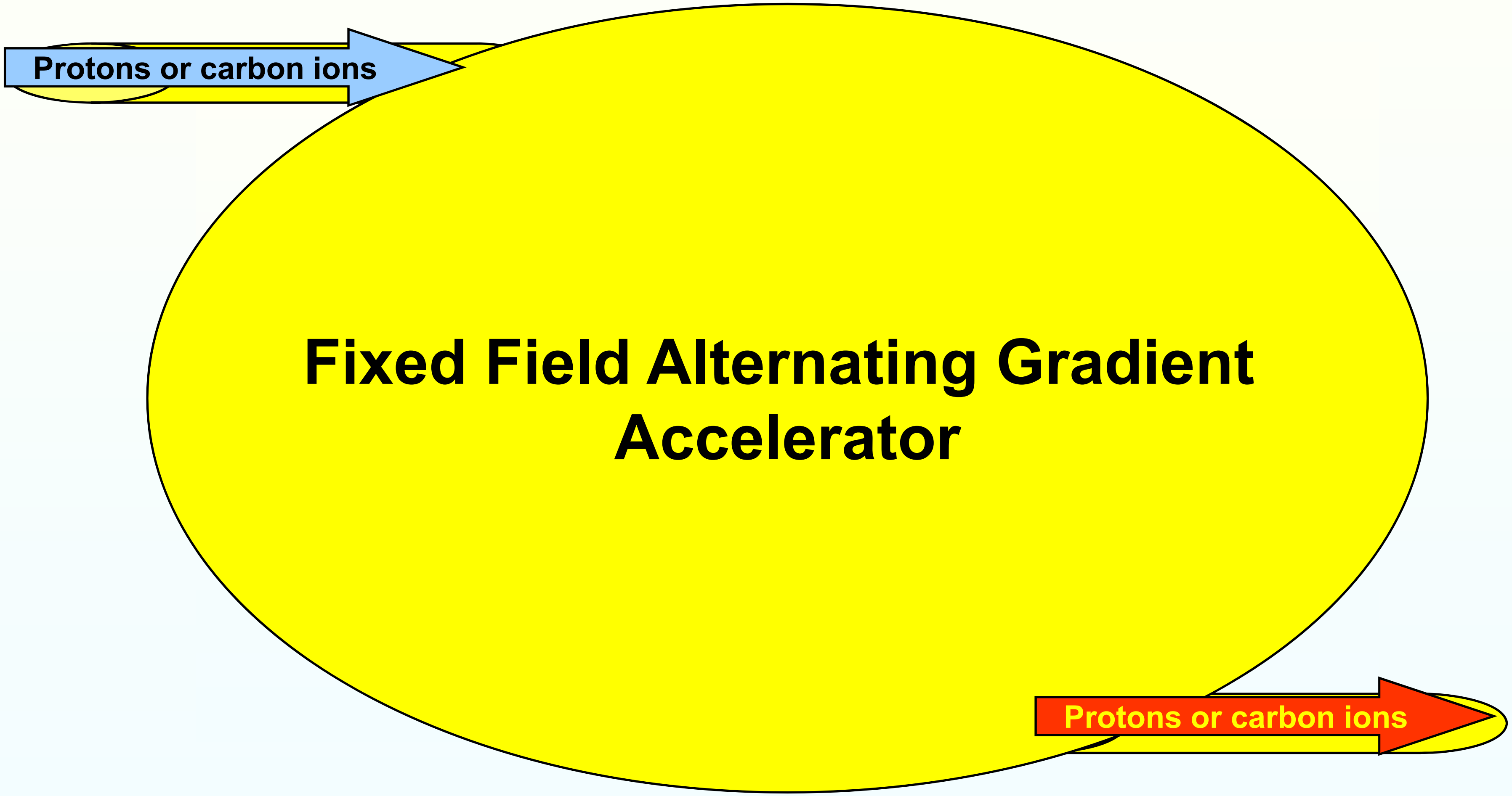
- The non-relativistic, non-scaling Fixed-Field Alternating Gradient Accelerator (nrns-FFAG) is a new type of accelerator
  - Very dense lattice
  - Challenging magnets, RF, injections and extraction
  - Resonance crossing
  - Stability
    - **EMMA will demonstrate the ns-FFAG**
    - **PAMELA will demonstrate the nrns-FFAG**

Status

- **Studies underway using a test lattice**
  - Magnets – probably combined function superconducting magnets
  - RF – a number of schemes are being considered
  - Injection and extraction – will constrain the lattice parameters
- **Aim**
  - Design a new lattice with a cell that can be engineered by end of 2008
  - Work through the design in 2009
  - Incorporate the lessons from EMMA
  - Produce a conceptual design in 2010

PAMELA

Particle **A**ccelerator for **ME**dical **A**pplications

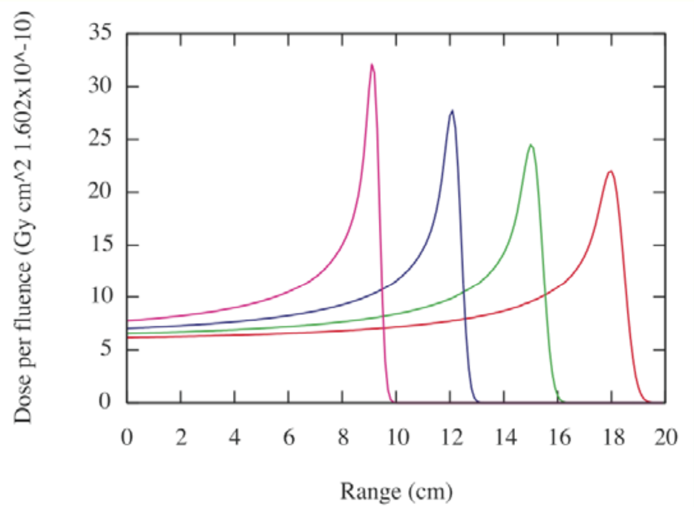


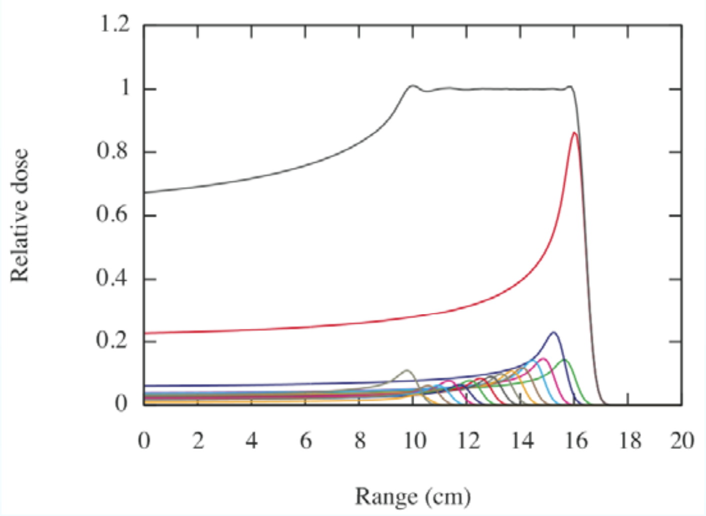
Protons or carbon ions

Fixed Field Alternating Gradient Accelerator

Protons or carbon ions

Medical Requirements

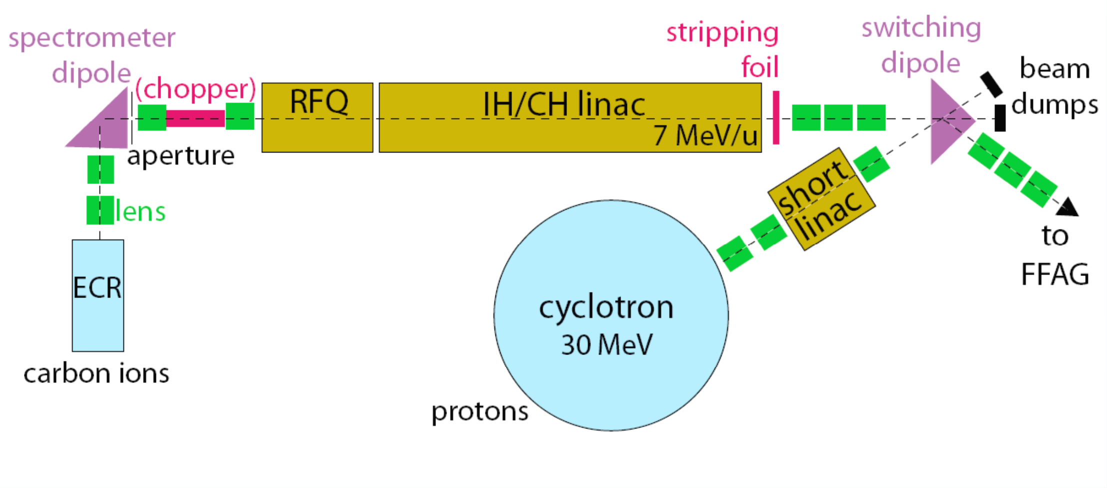




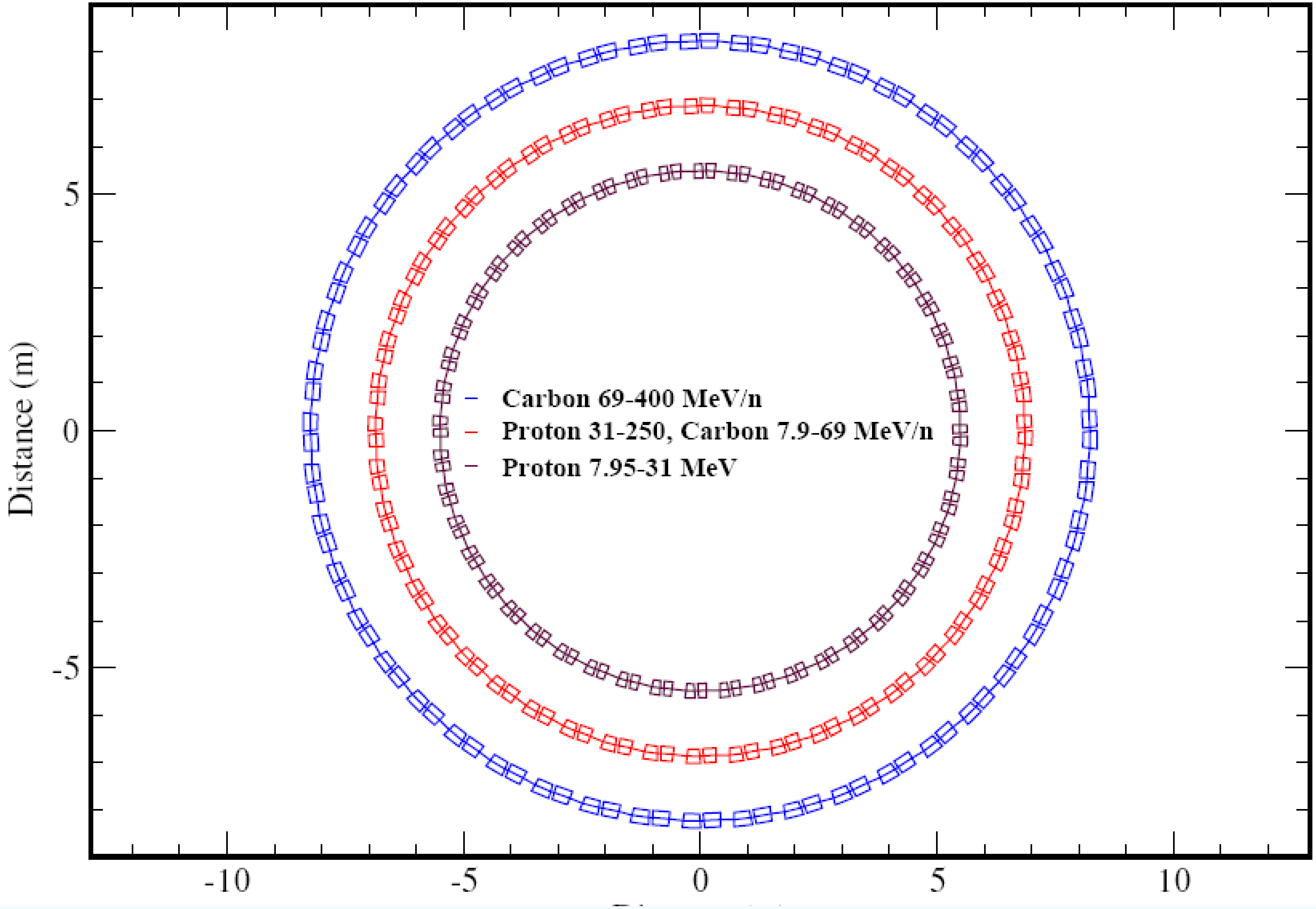
- SOBP in IMPT was studied using analytical model of Bragg peak
- Beam intensity quantization needs intensity modulation of 1/100 for dose uniformity of 2%.
  - (minimum pulse intensity:~10^6 proton/1Gy)
  - Monitor is a crucial R&D
- If 1kHz operation is achieved
  - > 100 voxel/sec can be scanned
  - 1 kHz repetition is a present goal (For proton machine : 200kV/turn)

Injector

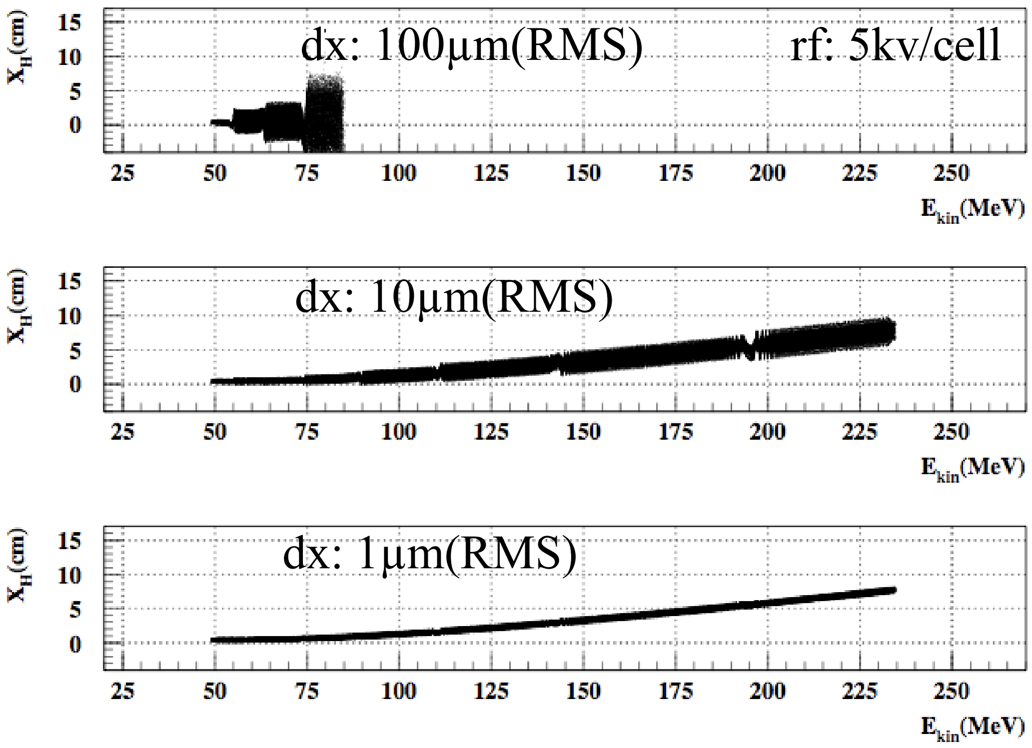
- Injector: proton and heavy ion injection
  - (IC group lead by J. Pozimsky)
  - Cyclotron for proton, RFQ for HI
  - Typical beam emittance from injectors:
    - 1π mm mrad (normalized)
- Tracking study of RFQ line in progress.
  - (transmission efficiency> 75% is achieved
  - 5% Stability of intensity



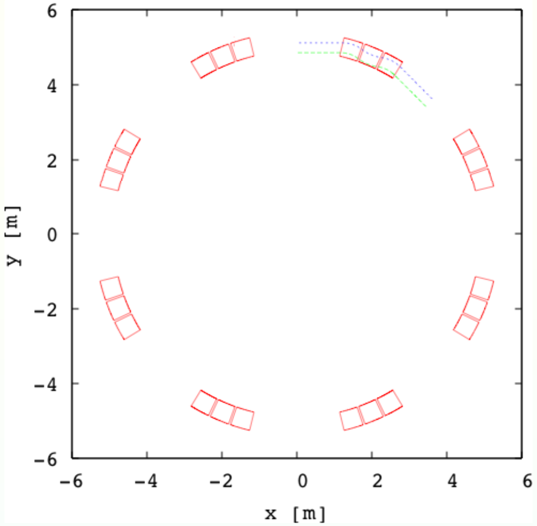
A Dense proton/carbon Lattice

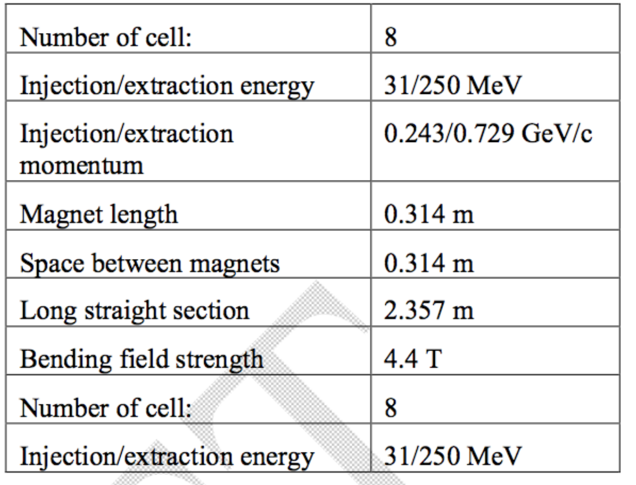


Acceleration studies



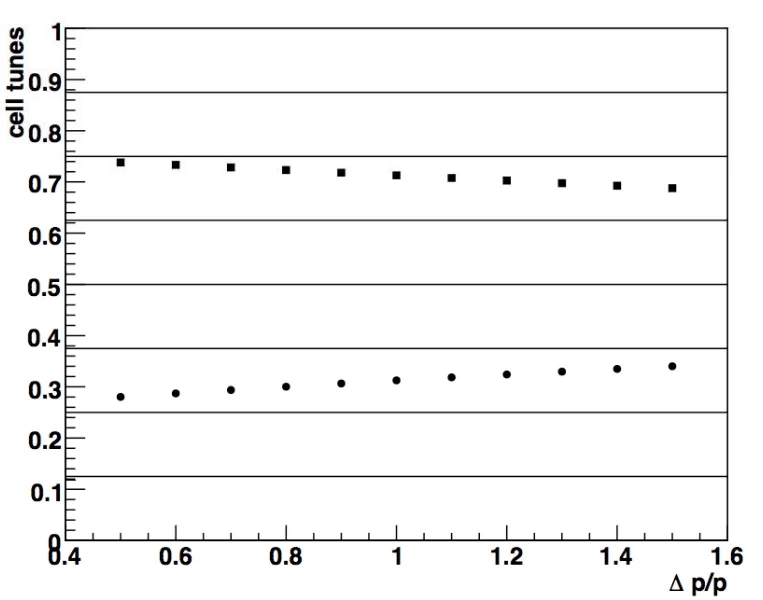
Lattice option





Number of cell:	8
Injection/extraction energy	31/250 MeV
Injection/extraction momentum	0.243/0.729 GeV/c
Magnet length	0.314 m
Space between magnets	0.314 m
Long straight section	2.357 m
Bending field strength	4.4 T
Number of cell:	8
Injection/extraction energy	31/250 MeV

S.Machida proposed semi-scaling FFAG for proton therapy (up to decapole)

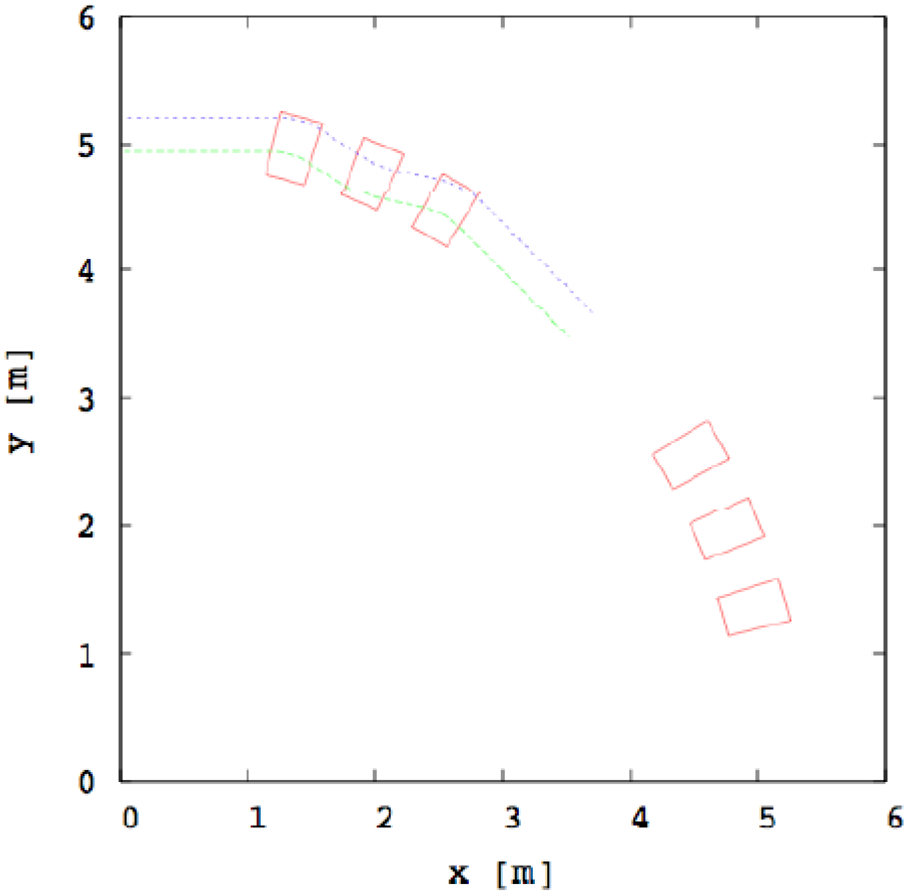


- Tune drift Δν<1 (No integer crossing, no structure resonance crossing)
- Orbit excursion ~30cm
- Long straight section (>2m)

⇒ H.Witte (magnet), S.Sheehy (Lattice)

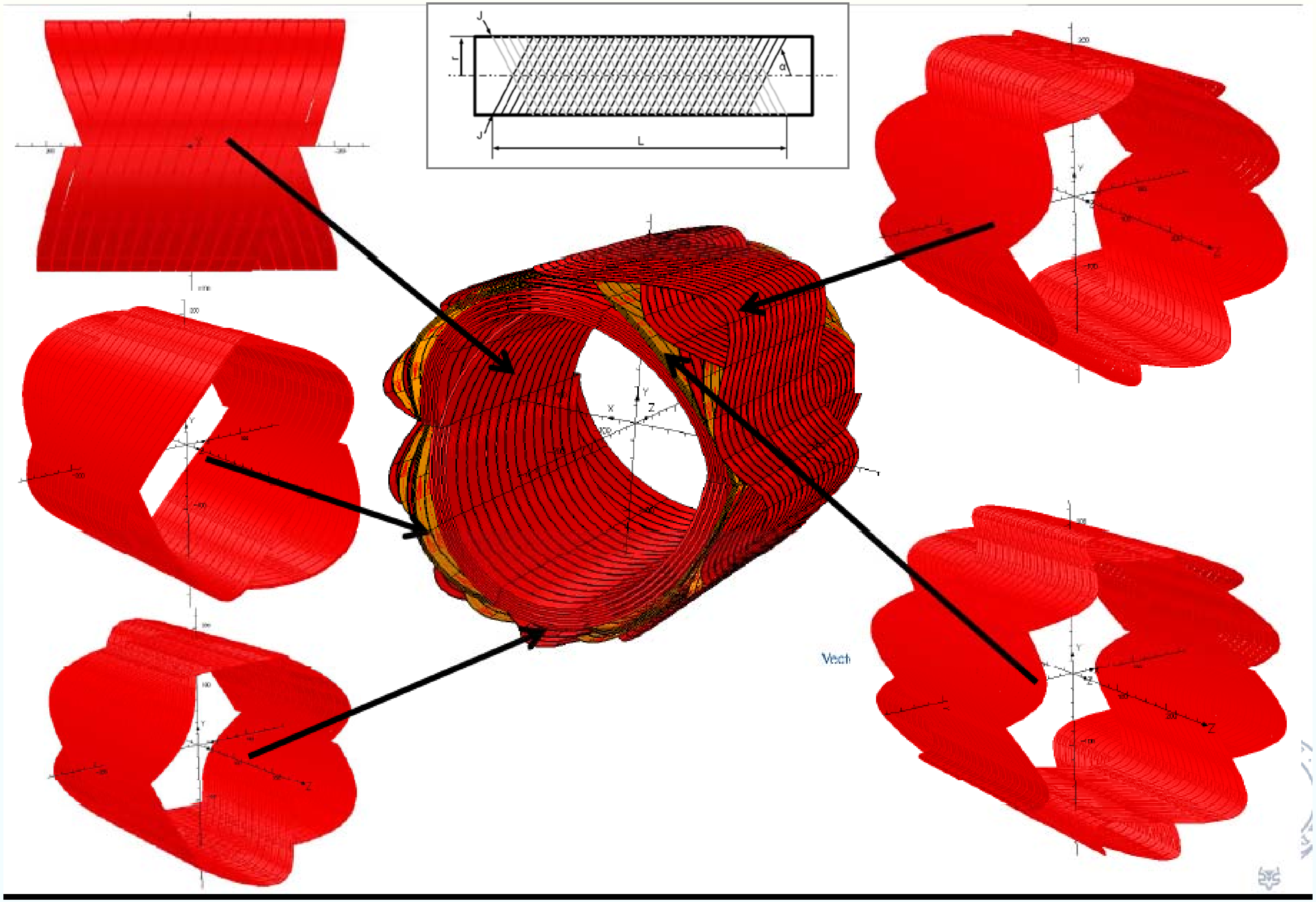
Magnets?

- Lattice by S. Machida
  - semi-scaling FFAG for proton therapy
- QF
  - Dipole 1T
  - Quad 4 T/m
  - Sextupole 0.76 T/m^2
  - Octupole 0.0912 T/m^3
  - Decapole 0.007752 T/m^4
- QD
  - 80% of QF
- Envisaged coil length: 0.314 m
- Additional Space: 0.314 m between magnets
- Maximum coil length: 0.45 m?
- Focus on **QF** (worst case)



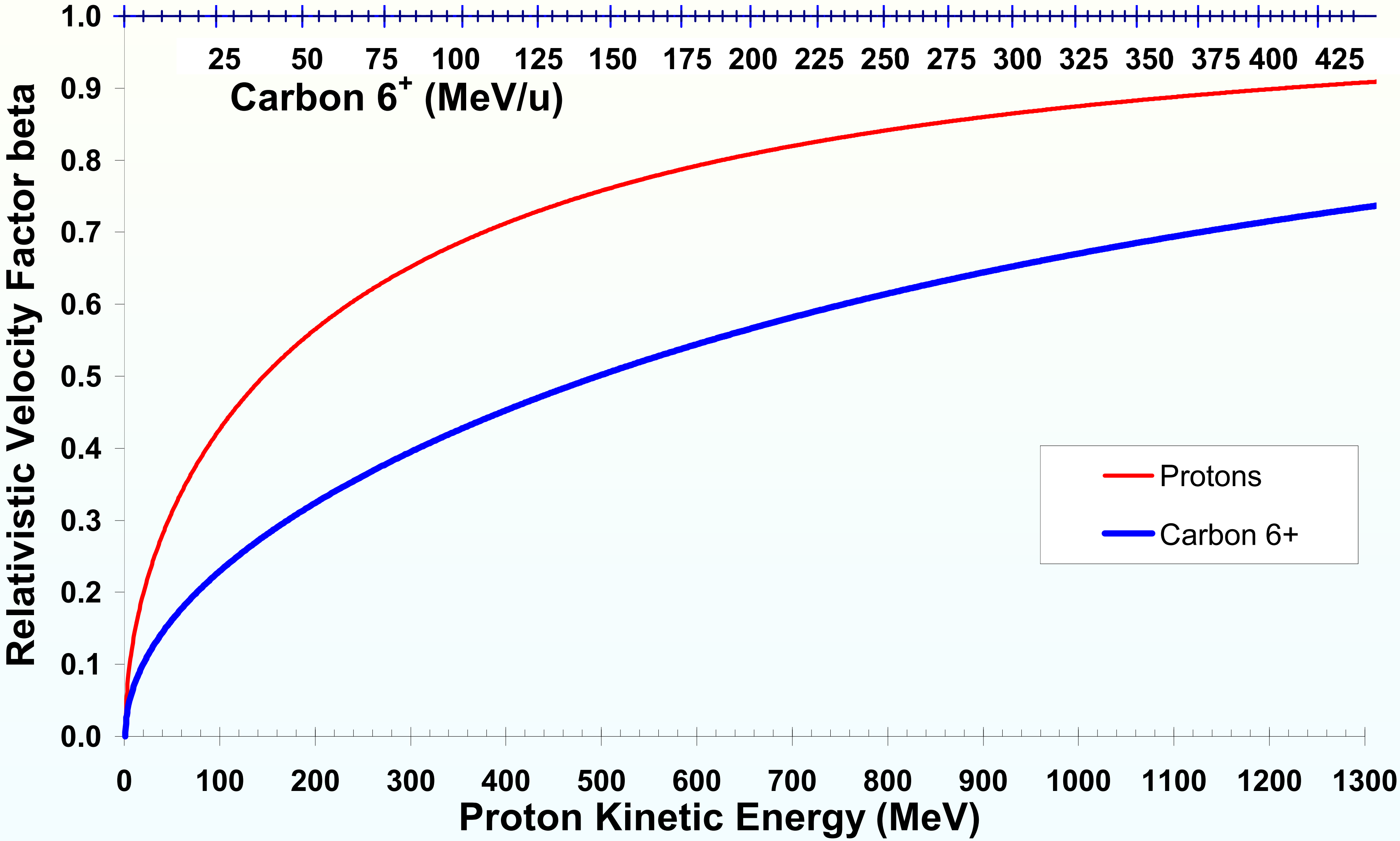
4.4 T with 314 mm space

Double helix magnet concept



RF

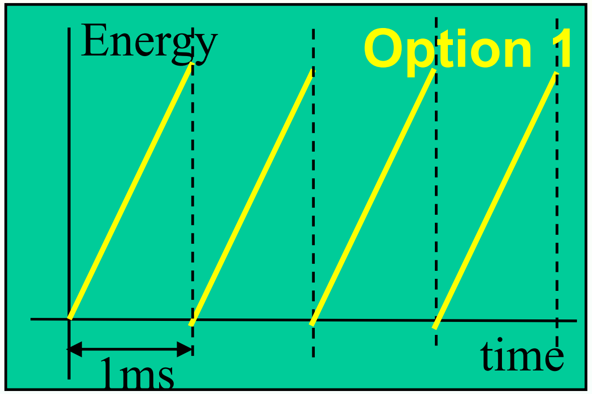
Relativistic Velocity Factor vs Energy

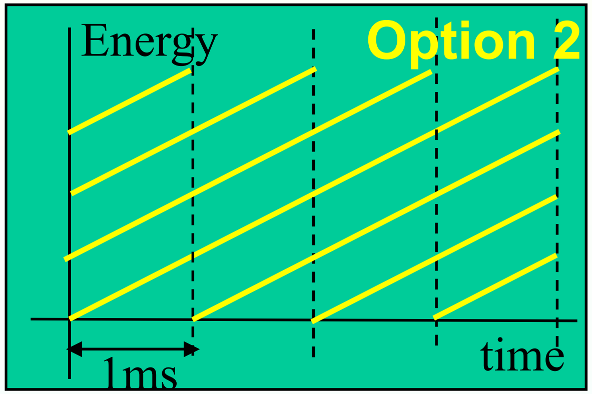


Acceleration schemes

Repetition rate: 1kHz ⇔ min. acceleration rate : 50kV/turn (=250Hz)

⇒ How to bridge two requirements ??





Low Q cavity (ex MA) can mix wide range of frequencies

$$P = \int \frac{(\Sigma V)^2}{R} dt$$

$$\begin{aligned}(\Sigma V)^2 &\equiv (\Sigma V_i sin[f_i(t)])^2 \\ &= \sum_i (V_i sin[f_i(t)])^2 + \underbrace{\sum_{i\neq j}(V_i sin[f_i(t)]\cdot V_j sin[f_j(t)])}_{\int dt \longrightarrow 0}\end{aligned}$$

⇒

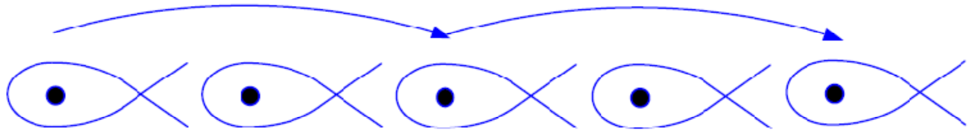
Option 1: $P \propto N_{rep}^2$

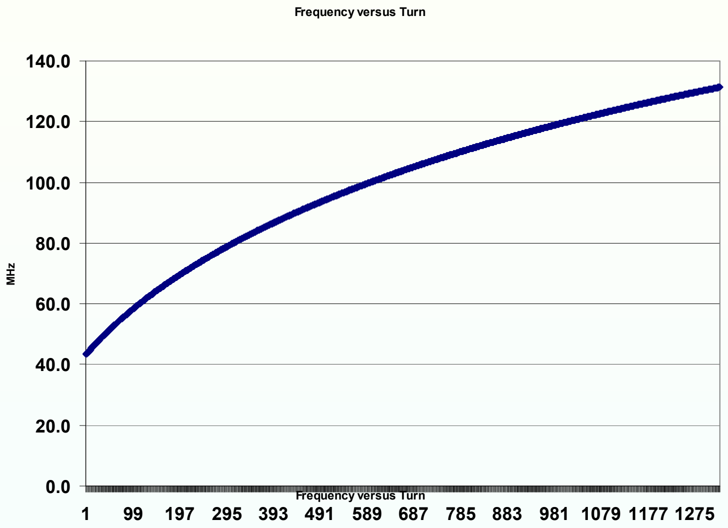
Option 2: $P \propto N_{rep}$

Multi-bunch acceleration is preferable from the viewpoint of efficiency and upgradeability

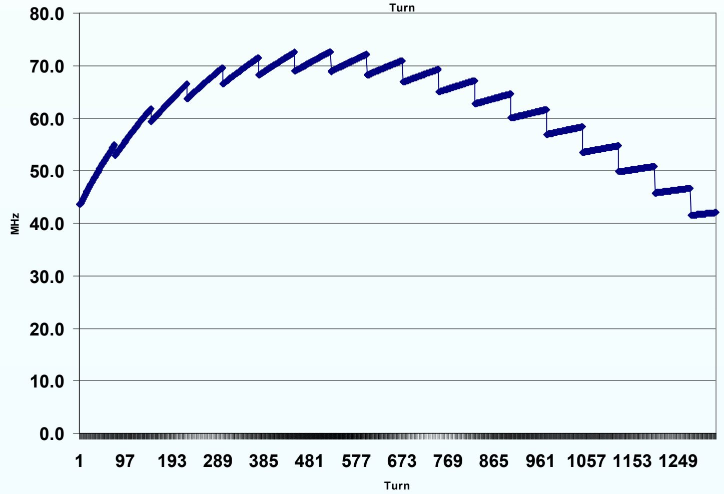
RF Issues

- Variable cyclotron frequency
  - RF schemes
    - Harmonic jump





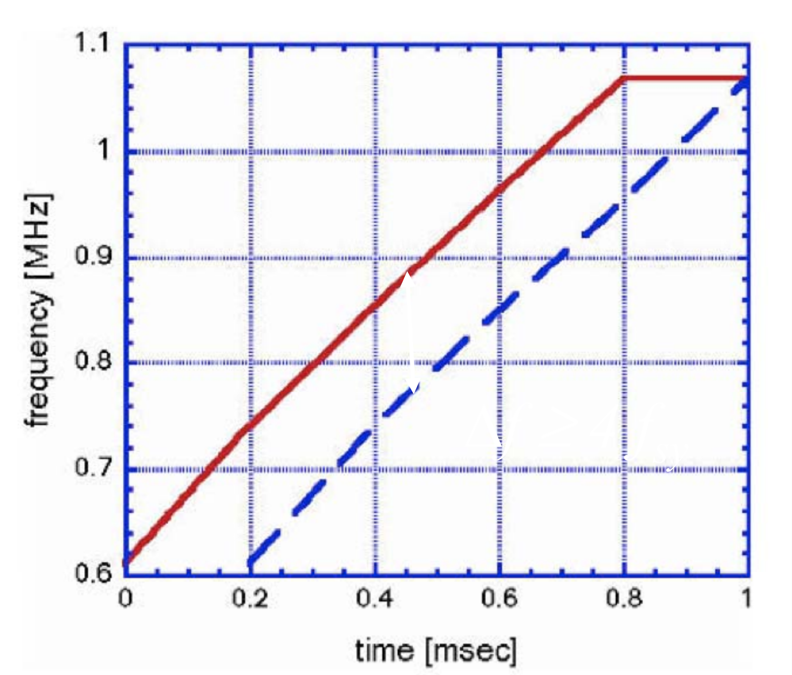
    - Variable frequency

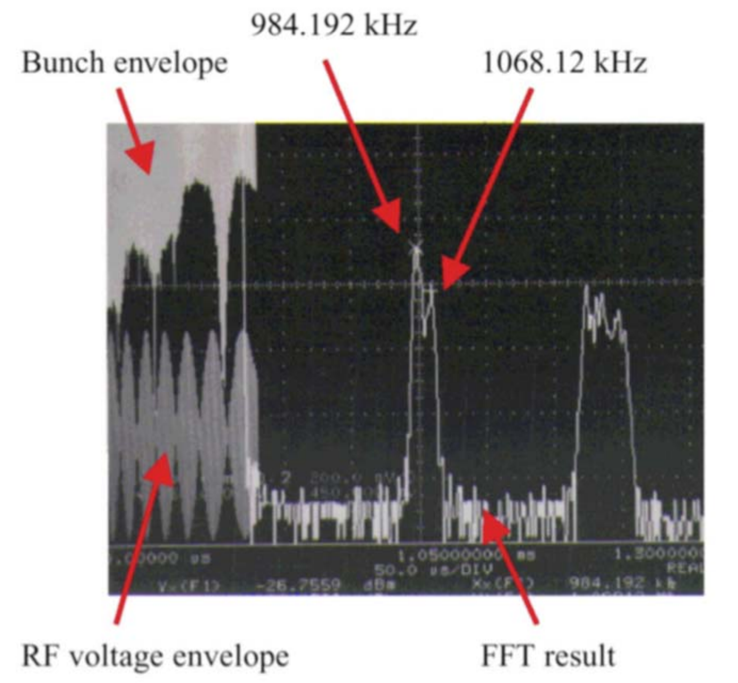


    - Variable voltage/phase
      - Try to vary the acceleration rate to reduce the frequency sweep

Multi-bunch Acceleration

Multi-bunch acceleration has already been demonstrated





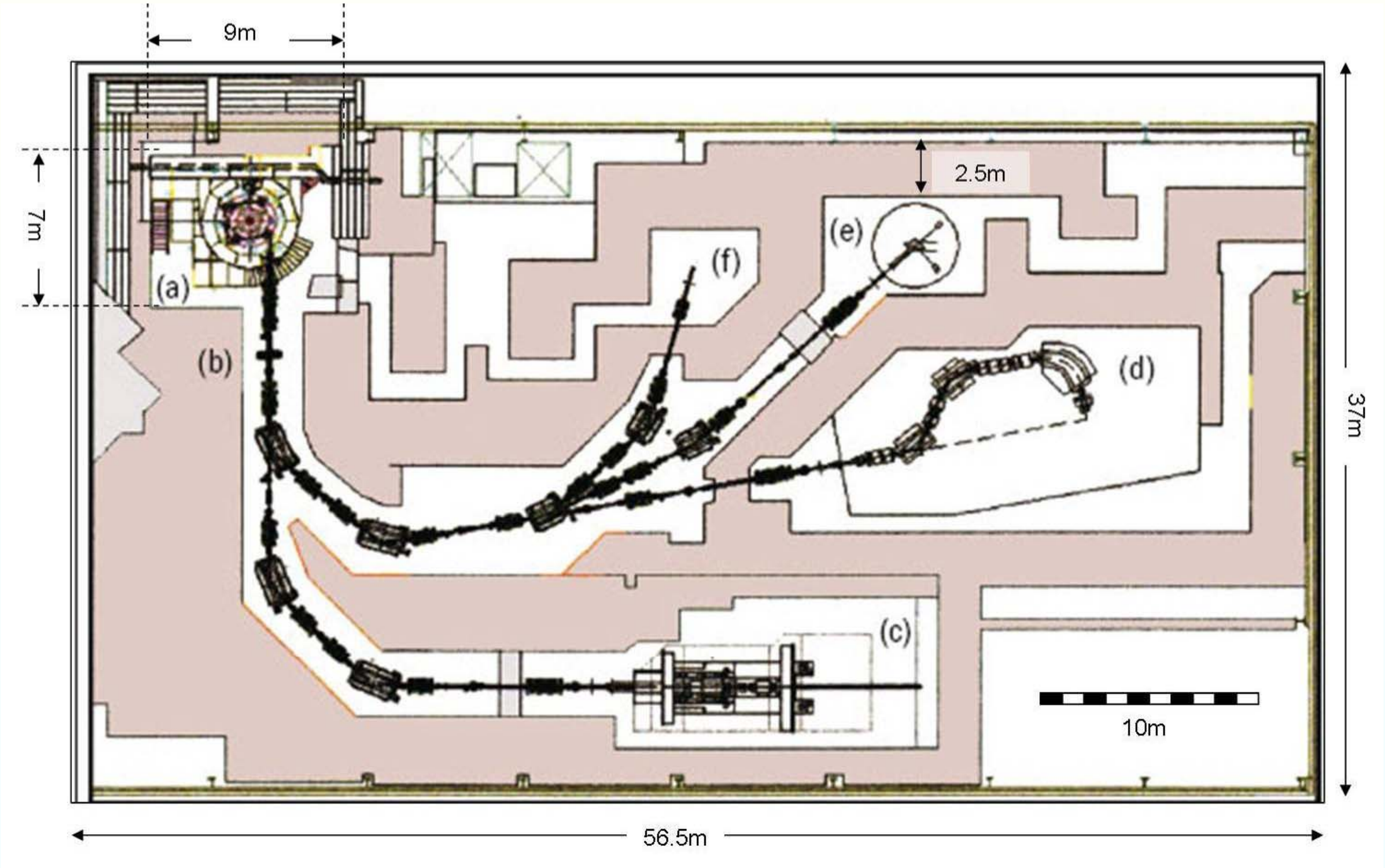
2-bunch acceleration using POP-FFAG (PAC 01 proceedings p.588)

Typical synchrotron tune <0.01

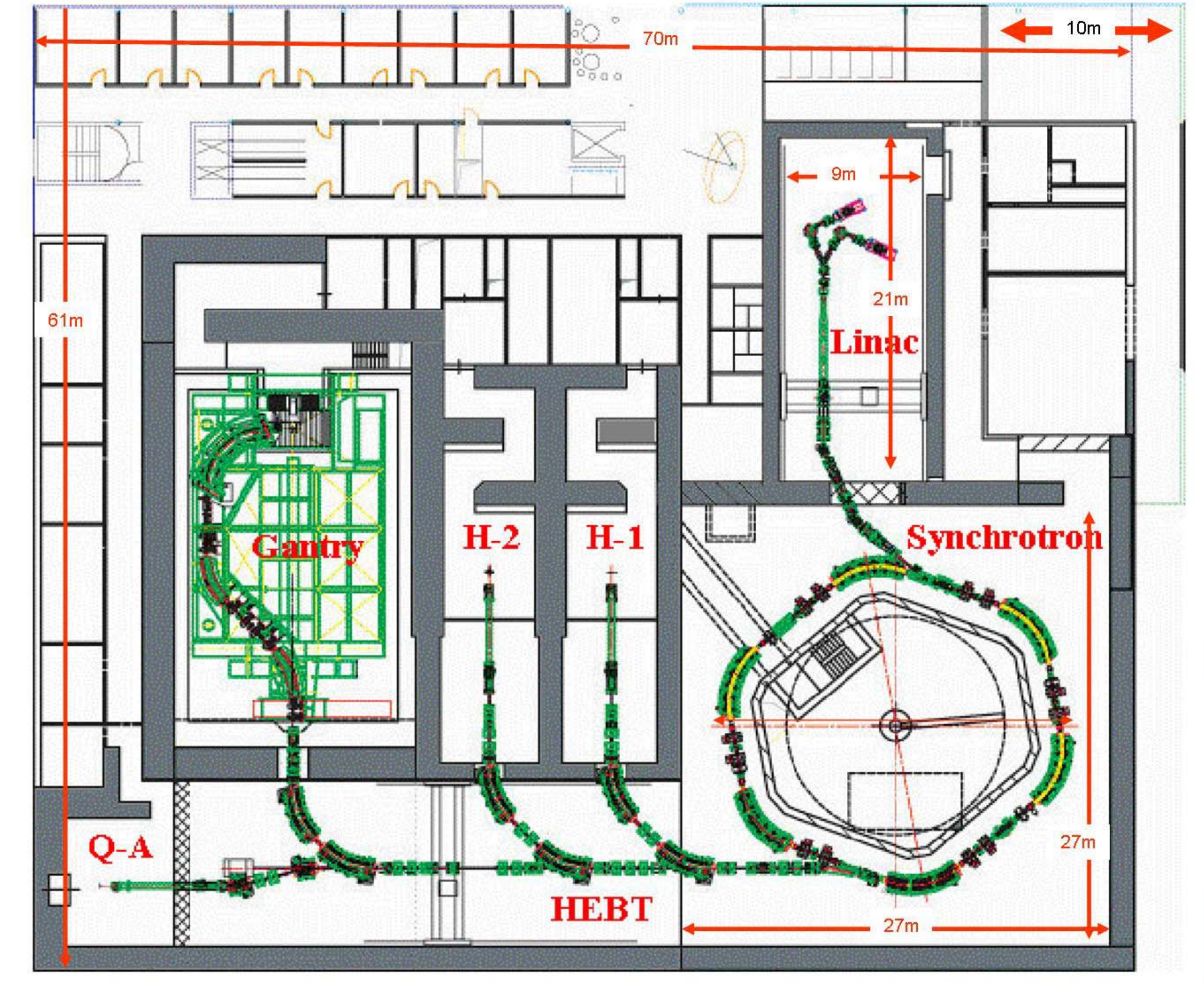
⇒ more than 20 bunches can be accelerated simultaneously

“Hardware-wise, how many frequencies can be superposed ??”

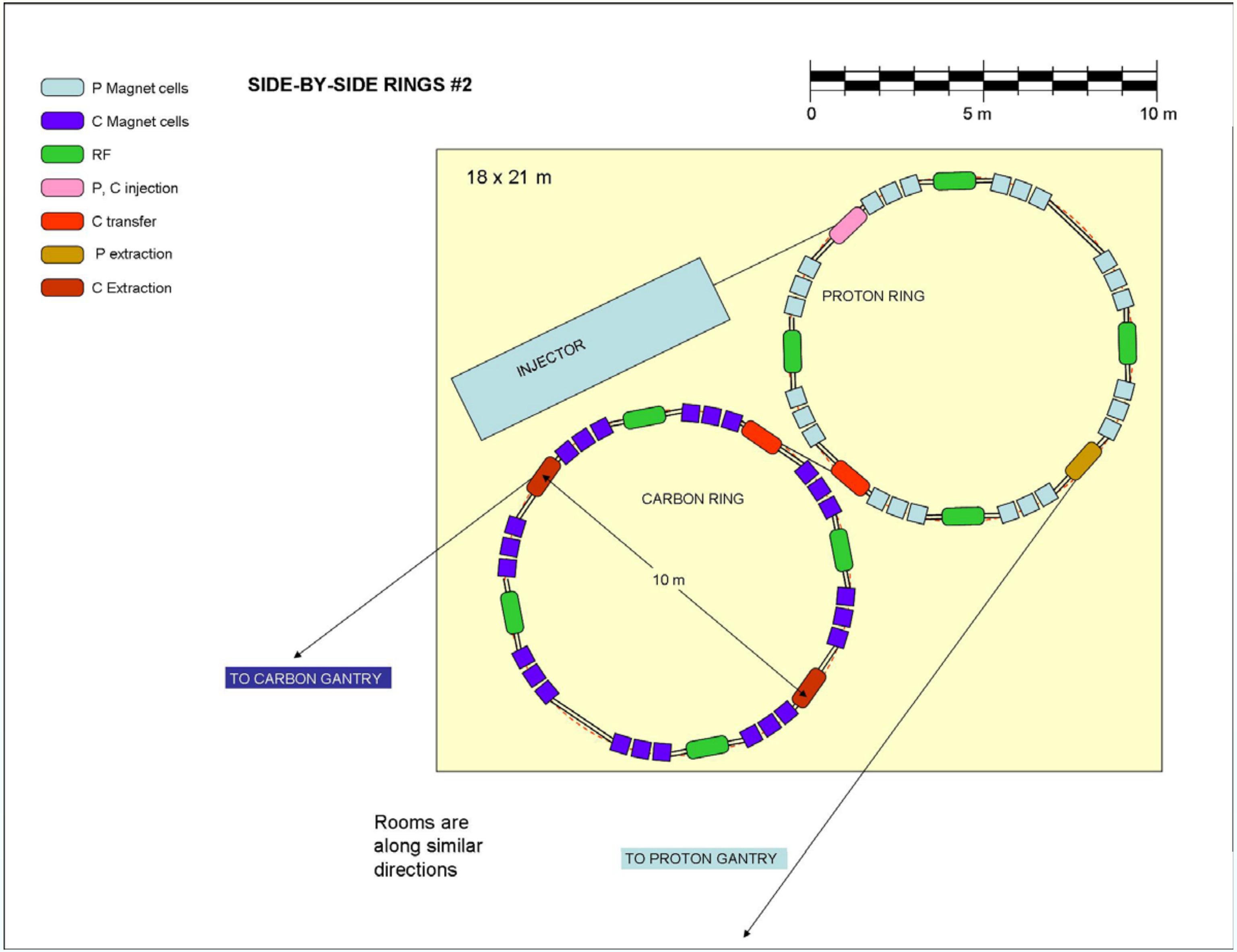
Civil Engineering and Layout - PSI



Civil Engineering and Layout - HIT

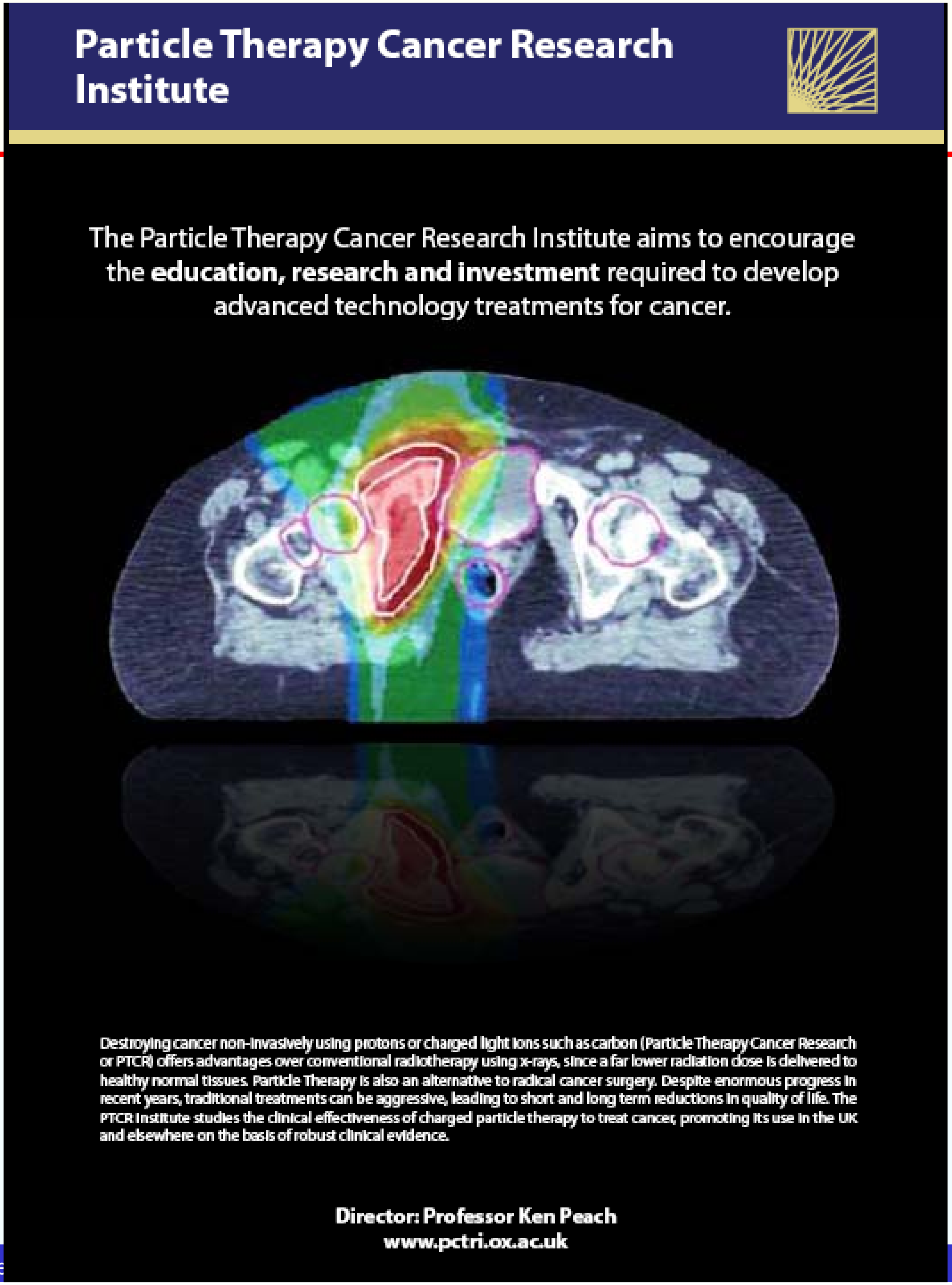


PAMELA



SIDE-BY-SIDE RINGS #2

Rooms are
along similar
directions



Particle Therapy Cancer Research Institute

The Particle Therapy Cancer Research Institute aims to encourage the **education, research and investment** required to develop advanced technology treatments for cancer.

Destroying cancer non-invasively using protons or charged light ions such as carbon (Particle Therapy Cancer Research or PTCR) offers advantages over conventional radiotherapy using x-rays, since a far lower radiation dose is delivered to healthy normal tissues. Particle Therapy is also an alternative to radical cancer surgery. Despite enormous progress in recent years, traditional treatments can be aggressive, leading to short and long term reductions in quality of life. The PTCR Institute studies the clinical effectiveness of charged particle therapy to treat cancer, promoting its use in the UK and elsewhere on the basis of robust clinical evidence.

Director: Professor Ken Peach
www.pctri.ox.ac.uk

Accelerator Driven Sub-critical Reactors (ADSR)

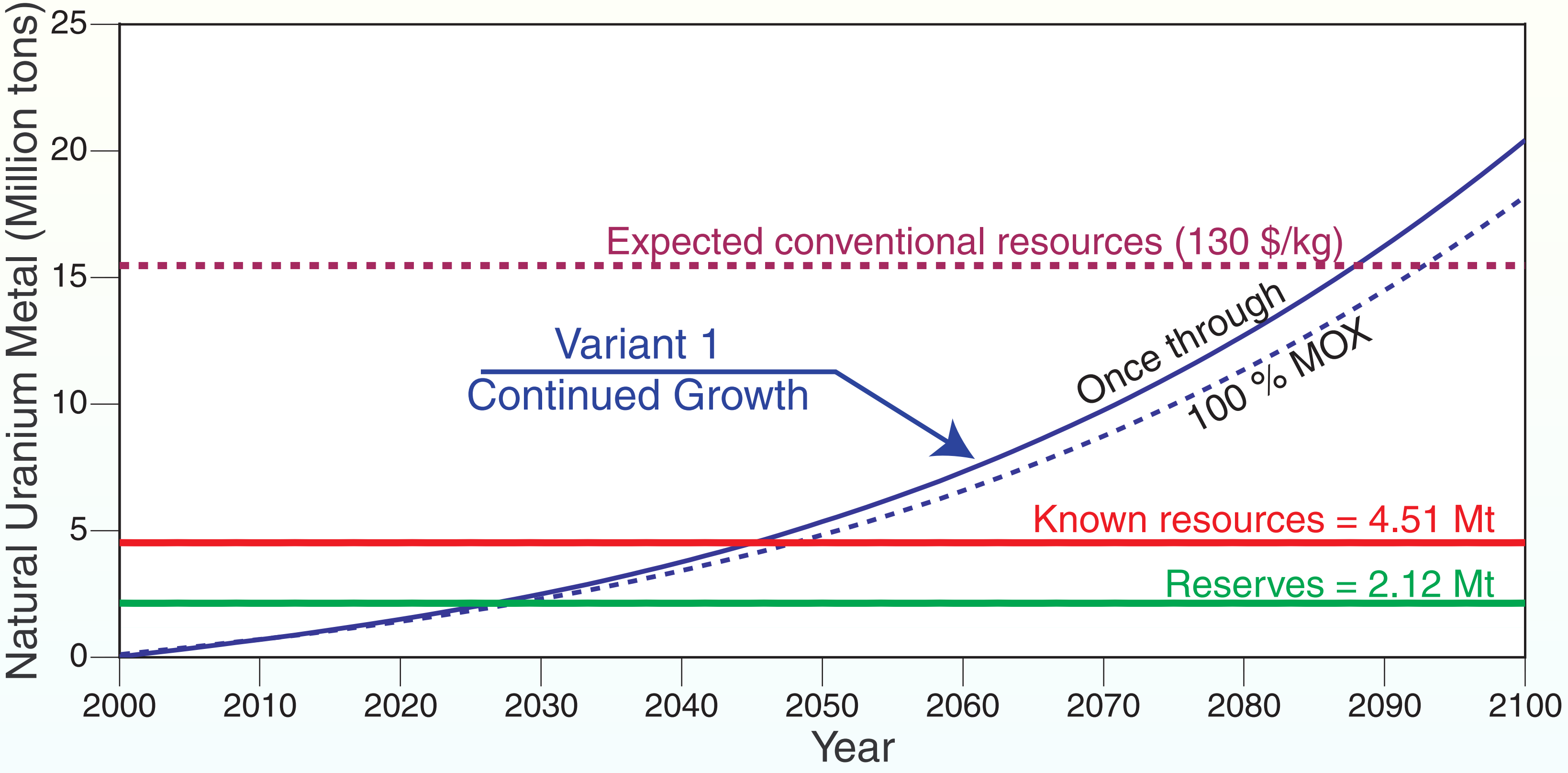
http://www.adams-institute.ac.uk http://www.basroc.org.uk Ken.Peach@adams-institute.ac.uk

Accelerator Driven Sub-critical Reactors (ADSR)

- Unlike ^{235}U, pure ^{238}U and ^{233}Th cannot be made into a critical mass
- However, in the presence of an external source of neutrons, both ^{238}U and ^{233}Th are fissionable
- But ^{238}U inevitably produces ^{239}Pu
  - Proliferation …
- ^{233}Th does not
- ^{233}Th is the 39th most abundant element
  - 7.2 parts per million (ppm) in the Earth's crust

Another issue – Uranium supplies

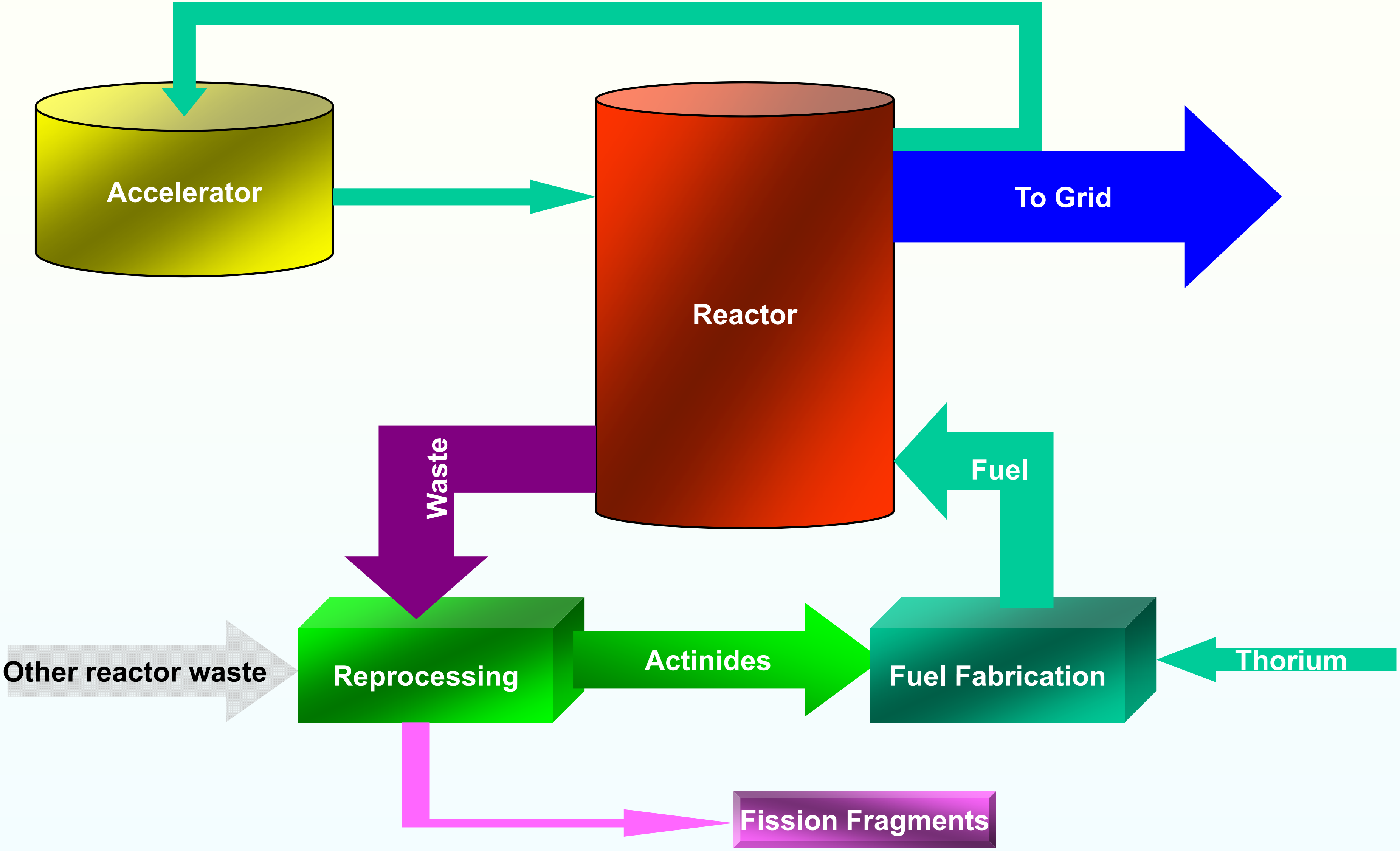
Cumulative natural Uranium demand and resource levels (Million ton U)



- **Kyoto Nuclear Scenarios Variant 1**

After Y Kadi, CERN

A Basic ADSR Power Plant Schematic



After Y Kadi, CERN

ADSR opportunities & risks

- ADSR is intrinsically “safe”
  - No plutonium
  - Sub-critical – stops if no neutron source
  - Abundant fuel
  - Treats actinides from ~ 4 nuclear reactors
- Major ADSR-specific technical risks
  - Accelerator reliability
    - Needs > 99% availability
    - No unscheduled interruptions > 1 second
  - Beam window(s)
    - Proton beam penetrates the reactor vessel
    - Containment
  - Spallation target power density
    - Multi-MW

ADSR Projects

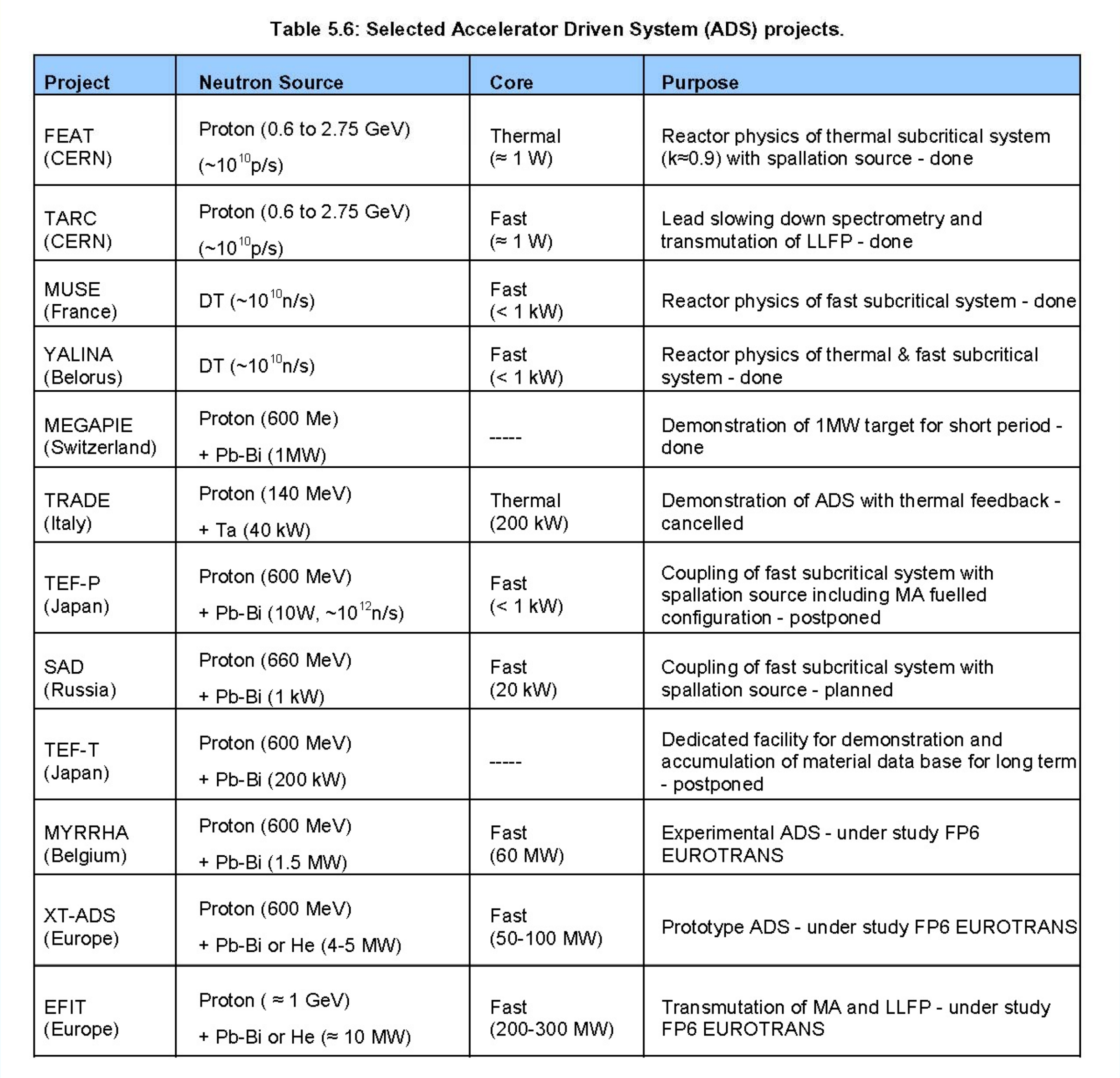


Table 5.6: Selected Accelerator Driven System (ADS) projects.

Project	Neutron Source	Core	Purpose
FEAT (CERN)	Proton (0.6 to 2.75 GeV) (~10^{10}p/s)	Thermal (≈ 1 W)	Reactor physics of thermal subcritical system (k≈0.9) with spallation source - done
TARC (CERN)	Proton (0.6 to 2.75 GeV) (~10^{10}p/s)	Fast (≈ 1 W)	Lead slowing down spectrometry and transmutation of LLFP - done
MUSE (France)	DT (~10^{10}n/s)	Fast (< 1 kW)	Reactor physics of fast subcritical system - done
YALINA (Belorus)	DT (~10^{10}n/s)	Fast (< 1 kW)	Reactor physics of thermal & fast subcritical system - done
MEGAPIE (Switzerland)	Proton (600 Me) + Pb-Bi (1MW)	-----	Demonstration of 1MW target for short period - done
TRADE (Italy)	Proton (140 MeV) + Ta (40 kW)	Thermal (200 kW)	Demonstration of ADS with thermal feedback - cancelled
TEF-P (Japan)	Proton (600 MeV) + Pb-Bi (10W, ~10^{12}n/s)	Fast (< 1 kW)	Coupling of fast subcritical system with spallation source including MA fuelled configuration - postponed
SAD (Russia)	Proton (660 MeV) + Pb-Bi (1 kW)	Fast (20 kW)	Coupling of fast subcritical system with spallation source - planned
TEF-T (Japan)	Proton (600 MeV) + Pb-Bi (200 kW)	-----	Dedicated facility for demonstration and accumulation of material data base for long term - postponed
MYRRHA (Belgium)	Proton (600 MeV) + Pb-Bi (1.5 MW)	Fast (60 MW)	Experimental ADS - under study FP6 EUROTRANS
XT-ADS (Europe)	Proton (600 MeV) + Pb-Bi or He (4-5 MW)	Fast (50-100 MW)	Prototype ADS - under study FP6 EUROTRANS
EFIT (Europe)	Proton (≈ 1 GeV) + Pb-Bi or He (≈ 10 MW)	Fast (200-300 MW)	Transmutation of MA and LLFP - under study FP6 EUROTRANS

From the *Thorium Report Committee of the Research Council of Norway* February 2008

Accelerator requirements

Proton Energy ~ 1 GeV

For 1GW thermal power:

- **Need 3 10^{19} fissions/sec (200 MeV/fission)**
- **6 10^{17} spallation neutrons/sec (k=0.98 gives 50 fissions/neutron)**
- **3 10^{16} protons/sec (20 spallation neutrons each)**

Current 5 mA. Power = 5 MW

Compare: PSI proton cyclotron:

590 MeV, 72 MeV injection

2mA, 1MW

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Specification

Cyclotron

Energy too high for classical cyclotron. On the edge for other types

Synchrotron

Current far too high.

Complicated (ramping magnets)

Linac

Can do the job. But VERY expensive

FFAG

Looks like the answer

Similar to proton therapy except higher current and no need for variable energy extraction

Very similar to neutrino factor proton driver

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Reliability

- No long shutdowns – lose money
- No unplanned shutdowns – lose money and customers
- Spallation target runs hot. If beam stops, target cools and stresses and cracks: no more than 3 trips per year

Cars and planes achieve this…

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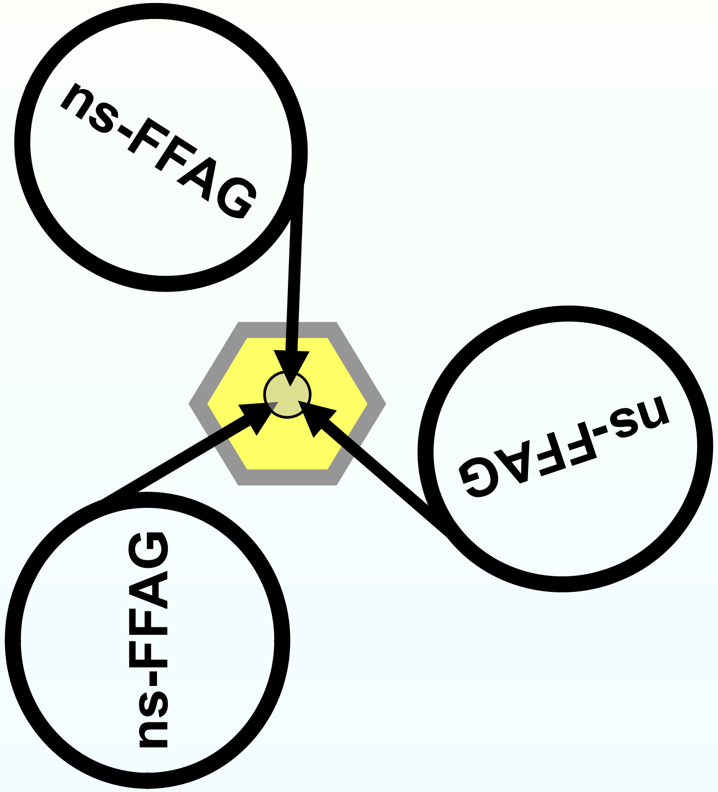
The ultimate redundancy

Could have several (3) accelerators for one reactor core

If FFAGs are really as cheap as we're promising



After **Roger Barlow/FFAG 08**

Summary

- Non-scaling FFAG accelerators are:
  - New
  - Untried
  - Interesting for
    - Neutrino physics
    - Cancer therapy
      - And other applications
        - » Spallation neutron sources, muon sources
        - » Accelerator driven reactors, nuclear waste disposal
- We will know in ~3 years if they work
  - Let us hope that they do … they could be very useful devices …

In memoriam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